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RESEARCH MEMORANDUM

EFFECT OF INLET TEMPERATURE AND HUMIDITY ON THRUST AUGMENTATION OF TURBOJET ENGINE BY COMPRESSOR-INLET INJECTION

By Thomas B. Shillito and James L. Harp, Jr.

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
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SUMMARY

An investigation has been conducted at conditions of zero ram and sea-level pressure to determine the effect of inlet temperature and humidity on turbojet-engine performance with injection of water and water-alcohol mixtures at the compressor inlet. The inlet-air temperature was varied by mixing atmospheric air with exhaust gases recovered from the exhaust jet of the engine, and the inlet humidity was varied by evaporating water in the exhaust gas used for heating the inlet air. It was found that at a given engine speed and tail-pipe temperature, both the thrust and total mass flow for the complete range of compressor-inlet temperatures, composition of injected mixtures, and injected flows investigated were functions only of the compressor-pressure ratio. The pressure ratio, and hence the augmented thrust, increased with injected flow and at a constant injected flow decreased with compressor-inlet temperature. The effect of inlet temperature on compressor pressure ratio and thrust became less pronounced as compressor-inlet injected flow increased. The augmented thrust ratio increased with compressor-inlet temperature at a constant total liquid flow. At a total liquid flow of 5 pounds per second, the augmented thrust ratio obtained at rated engine speed and tail-pipe gas temperature (as permitted by use of a variable-area exhaust nozzle) increased from 1.26 to 1.62 as the compressor-inlet temperature was increased from 60° F to 200° F. At a given inlet temperature and injection rate, the thrust decreased slightly with increasing humidity, the effects being more pronounced at the higher injection rates.

INTRODUCTION

A simple method of increasing the thrust of turbojet engines is by the injection of refrigerants at the compressor inlet. The results of experimental investigations of this method of thrust augmentation for centrifugal-flow engines, which included the injection of water and water-alcohol mixtures, are reported in references 1 and 2. These investigations, however, were conducted without control of inlet temperature or humidity. An investigation, therefore, has been conducted to determine the effect of compressor-inlet temperature and humidity on engine performance with injection at the compressor inlet, and the results are reported herein.

For this investigation, which was conducted at conditions of zero ram and sea-level pressure, the inlet temperature was controlled by mixing atmospheric air with exhaust gases recovered from the exhaust jet of the engine used for the tests. By this method of heating, the compressor-inlet temperature was varied over a range from 60° F to 230° F. The performance of the engine was determined for no injection and over a range of injection rates from 1 to 4 pounds per second for various mixtures of water and alcohol. Both fixed-area and variable-area tail-pipe exhaust nozzles were used. Rated engine speed and tail-pipe temperature were maintained for all operating conditions while using the variable-area nozzle, and, depending on operating conditions, either rated speed or rated tail-pipe temperature was maintained while using the fixed-area nozzle. The effect of specific humidity of the inlet air on both unaugmented engine performance and engine performance at two injection rates was investigated over a range from 50 to 280 grains per pound at two compressor-inlet temperatures. For these tests, the inlet humidity was varied by evaporating water in the hot exhaust gases used for heating the inlet air.

APPARATUS

Engine. - The engine used in this investigation was a J33 centrifugal-flow turbojet engine with a sea-level, static-thrust rating of 4000 pounds when operated at a speed of 11,500 rpm and tail-pipe temperature of 1200° F. Both a 19-inch conical fixed-area and a clamshell-type variable-area exhaust nozzle were used.

Engine installation and bleedback system. - As shown in figure 1, the test equipment was enclosed in two adjacent chambers: a closed cell containing the engine proper, and a muffler into which the exhaust jet was discharged. The engine and inlet cowl were mounted on a frame suspended from the ceiling of the test cell by rods with ball-bearing ends, and the engine tail pipe moved freely through a sliding seal in the wall separating the cell and muffler.

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The mounting frame was thus free to move through a linkage system against the balancing cell of a thrust-measuring system, as shown in figure 1. The methods by which this system was used to determine jet thrust are outlined in appendix A. Also shown in figure 1 is the main air-flow measuring nozzle and the air-supply diffuser.

The equipment used to control the compressor-inlet temperature consisted of an exhaust-gas bleedback system in which part of the exhaust gases were bled back and mixed with the fresh-air charge in the test cell. Directly behind the engine exhaust nozzle was an exhaust gas bleedback scoop into which exhaust gas was rammed (fig. 2). The exhaust gas was bled back through a circular duct and was emitted just ahead of the inlet cowl through longitudinal slots on the inner surface of a scroll-shaped manifold (fig. 3). The bleedback exhaust flow was measured by means of a bellmouth measuring nozzle and the flow rate was controlled by a hydraulically actuated butterfly valve. A circular deflection plate slightly larger than the inside diameter and located approximately 8 inches ahead of the exhaust-gas outlet manifold aided the mixing process and prevented serious stratification of temperatures in the compressor-inlet charge.

Injection system. - Water and alcohol were injected into the two sides of the compressor inlet from separate manifolds, as shown in figure 4. Each manifold was equipped with 28 tubes (14 for each side of the compressor inlet) leading to commercial spray nozzles that were directed radially into the compressor inlet. Flow rates in each manifold were measured by means of calibrated sharp-edged orifices.

Fuel and injected liquids. - The fuel used in the engine was JP-1. The water injected into the compressor inlet was obtained from domestic supply lines and the alcohol was a mixture of 50-percent methyl and 50-percent ethyl by weight. The injected fluid ranged in composition from water alone to a mixture of 40-percent water and 60-percent alcohol by weight.

Humidifying system. - The water nozzles used to control the humidity of the inlet air were located in the bleedback duct approximately 12 inches downstream of the butterfly valve. Flow of this water was measured by means of a calibrated sharp-edged orifice.

Instrumentation. - Compressor-inlet temperatures were measured on four, five-thermocouple rakes spaced 90° apart and located in a plane cutting the front of the forward inlet of the compressor (fig. 4). These thermocouples were connected to give either five individual readings of a 4-point average at a given radius or a single reading of a 20-point average over the entire flow area. Compressor-discharge temperatures were measured on two, four-thermocouple rakes located in diametrically opposite combustion-chamber adapters. Engine exhaust-gas temperatures were measured on eight strut-type thermocouples located in a normal plane through and spaced at equal angles around the straight section of the engine tail pipe. Other temperature measurements included those of the main air supply in the measuring nozzle and the bleedback gas at the entrance to its measuring nozzle.

The static pressure inside the test cell was measured by a flush tap on the wall. Compressor-inlet total pressures were taken on four, five-tube rakes spaced equally around and in the same plane of the engine cowl as the inlet-temperature thermocouples. Compressor-discharge total pressures were measured on two, four-tube rakes located in diametrically opposite combustion-chamber adapters. Total pressures were measured on an eleven-tube rake across the tail-pipe diameter at a point approximately 24 inches ahead of the fixed-area nozzle discharge plane and approximately 36 inches ahead of the variable-area nozzle discharge plane. Static pressures in the muffler were measured in the vicinity of the exhaust-nozzle discharge and on the wall separating the test cell and muffler.

PROCEDURE

Investigation of performance parameters. - The first phase of the investigation consisted of an experimental verification of the performance parameters used to generalize jet-engine performance data. For this phase, the engine was equipped with a 19-inch-diameter fixed-area conical nozzle and operated normally (no injection) over the range of engine speeds and compressor-inlet temperatures indicated in the following table:

Indicated engine speed (rpm)	Average compressor-inlet temperature (°F)
8,900	66, 87, 127, 160, 182
10,000	68, 91, 126, 161
10,500	161
11,000	70, 92, 126
11,250	70, 95, 125
11,300	125
11,500	71, 93

The spread of individual temperatures measured at the compressor inlet did not exceed ±15° F for the conditions in the preceding table or for any other conditions covered in the present investigation.

For this and all other phases of the investigation except the variable inlet-humidity runs, the inlet humidity was not controlled and varied from 35 to 115 grains per pound of air.

Augmented engine performance with variable-area exhaust nozzle. - The effect of inlet temperature on thrust augmentation for operation with a variable-area exhaust nozzle was investigated for injection of several water-alcohol mixtures at the compressor inlet. The following table summarizes the conditions covered during these tests:

Indicated engine speed (rpm)	Tail-pipe temperature (°F)	Injected flow (lb/sec)	Water (percent by weight)	Alcohol (percent by weight)	Compressor-inlet temperature (°F)
11,500	1200	0	----------	----------	61-200
11,500	1200	1	100	0	57-198
11,500	1200	2	100	0	57-196
11,500	1200	3	100	0	109-193
11,330	1200	3	100	0	73
11,500	1200	2	80	20	71-209
11,500	1200	4	80	20	73-216
11,500	1200	2	60	40	72-185
11,500	1200	3	60	40	72-199
11,500	1200	4	60	40	73-174
11,500	1200	2	40	60	80-212
11,500	1200	3	40	60	87-173
11,500	1200	4	40	60	88-230

The runs with zero injected flow were made for the determination of normal engine performance on which to base the thrust augmentation obtainable through injection. These runs were made at frequent intervals throughout the investigation to provide, if necessary, a time history of decrease in engine-performance efficiency.

All runs with the variable-area nozzle were conducted at a limiting engine speed of 11,500 ±75 rpm and limiting tail-pipe temperature of 1200 ±10° F, except for the injection of 3 pounds per second of 100-percent water and inlet temperatures below about 110° F where the engine fuel system was of insufficient capacity to maintain speed.

Injection rates above 3 pounds per second with water alone were not investigated because of combustion blowout that was encountered on several occasions at injection rates of about 3.5 pounds per second.

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Augmented engine performance with fixed-area exhaust nozzle. - The effect of inlet temperature on thrust augmentation for operation with a fixed-area exhaust nozzle was investigated for the injection of water alone at the compressor inlet. The following table summarizes the conditions covered during these tests:

Indicated engine speed (rpm)	Tail-pipe temperature (°F)	Injected flow (lb/sec)	Water (percent by weight)	Alcohol (percent by weight)	Compressor-inlet temperature (°F)
11,500 or below	1200 or below	0	----------	----------	85-137
"	"	1	100	0	89-168
"	"	2	100	0	94-180
"	"	3	100	0	99-178

At a given injection rate with the fixed-area exhaust nozzle, operation at simultaneous limiting conditions of engine speed and tail-pipe temperature was possible only for one inlet temperature. Consequently, operation with the fixed nozzle was limited to either a speed of 11,500 rpm and reduced tail-pipe temperature, or a tail-pipe temperature of 1200° F and a reduced engine speed, depending on the injection rate and inlet temperature. The exact limits of operation will be further illustrated and discussed in a subsequent section.

Effect of humidity. - The following table summarizes the conditions covered during the investigation of the effects of inlet-air humidity:

Compressor-inlet temperature (°F)	Injected water flow (lb/sec)	Humidity (grains/lb-air)
125	0	52-254
125	1	55-253
125	2	62-208
150	0	64-266
150	1	72-276
150	2	83-248

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During this investigation, the engine was equipped with the variable-area exhaust nozzle to permit operation at the limiting conditions of 11,500 rpm and 1200° F tail-pipe temperature. The injected fluid was 100-percent water and the injected flow was limited to 2 pounds per second because of the inability to maintain combustion at higher rates of injection for the higher range of humidities. The compressor-inlet humidity was determined from measurements of the flow of water injected into the bleedback duct, the bleedback exhaust flow, the fuel flow, the water injected into the compressor inlet (the portion recirculated), and wet and dry bulb temperatures inside the test cell. Details of the method used to determine the humidity are outlined in appendix B.

SYMBOLS

The following symbols are used in this report:

A flow area, (sq in.)

c_p specific heat at constant pressure, (Btu)/(lb)(°R)

D compressor impeller diameter, (ft)

F jet thrust, (lb)

g acceleration of gravity, (ft/sec^2)

J mechanical equivalent of heat, 778 (ft)(lb)/(Btu)

K compressor slip factor, $= \dfrac{\text{work per pound} \times g}{\left(\dfrac{\pi DN}{60}\right)^2}$

N compressor or engine rotative speed, (rpm)

P total pressure, (lb)/(sq in. absolute)

p static pressure, (lb)/(sq in. absolute)

R gas constant, (ft-lb)/(lb)(°R)

T total temperature, (°R)

T' total temperature, (°F)

t static temperature, ($^{\circ}R$)

V velocity, (ft)/(sec)

W weight flow, (lb)/(sec)

γ ratio of specific heat at constant pressure to specific heat at constant volume

δ P/14.696

η adiabatic efficiency

θ T/518.4

ρ density, (lb)/(cu ft)

Subscripts:

a air

al alcohol (injected into compressor inlet)

b bleedback

f fuel

h water injected into bleedback system

N main air measuring nozzle

n exhaust nozzle

s superheated steam in the computation of humidity

T turbine

w water (injected into compressor inlet)

0 cowl inlet

1 compressor inlet

2 compressor discharge

3 burner inlet

4 burner exit

5 turbine-nozzle throat

6 turbine discharge

7 tail pipe ahead of exhaust nozzle

8 exhaust jet expanded to ambient pressure

The data obtained in the investigation of normal performance parameters for turbojet engines were generalized to obtain the following conventional parameters:

$\frac{N}{\sqrt{\theta_1}}$ corrected engine speed

$\frac{F}{\delta_1}$ corrected thrust

$\frac{W_f}{\delta_1 \sqrt{\theta_1}}$ corrected fuel flow

$\frac{T_7}{\theta_1}$ corrected tail-pipe temperature

In analyzing the data obtained in the investigation of augmented turbojet engine performance the compressor-inlet temperature, and hence θ_1, was retained as a prime variable and no generalizations involving θ_1 were attempted. The factor δ_1 was, however, included in the performance parameters to permit adjustment of values to a common inlet pressure of 14.696 pounds per square inch; generalization of these data for wide ranges of inlet pressure is not intended. For this investigation the following generalized or adjusted values were used:

$\frac{F}{\delta_1}$ adjusted thrust

$\frac{W_{al}}{\delta_1}$ adjusted alcohol flow

$\frac{W_w}{\delta_1}$ adjusted water flow

$\frac{W_f}{\delta_1}$ adjusted fuel flow

$\frac{W_a}{\delta_1}$ adjusted air flow

RESULTS AND DISCUSSION

Normal Engine Performance

The results of the runs to verify experimentally the generalized turbojet performance parameters are presented in figure 5. Corrected thrust F/δ_1, corrected fuel flow $W_f/\delta_1\sqrt{\theta_1}$, and corrected tail-pipe temperature T_7/θ_1 are plotted against corrected engine speed $N/\sqrt{\theta_1}$. The data for both variable speed and variable inlet temperature fall on a single curve for all parameters presented indicating that normal engine performance data may be generalized by use of the temperature correction θ_1 over a range of compressor-inlet temperatures from 70° F to 180° F. Data illustrating the application of these generalization methods for lower compressor-inlet temperatures are presented in reference 3. The range of compressor-inlet pressures covered by the data of figure 5 was too small to constitute an investigation of generalization by use of δ_1.

At a corrected engine speed of 11,500 rpm, the corrected thrust (fig. 5) was about 3400 pounds as compared with the nominal rating of 4000 pounds for this type engine. This lower thrust is attributable to use of an over-size exhaust nozzle, which resulted in a corrected tail-pipe temperature of 1620° R (40° F lower than the nominal 1200° F) and to the fact, as will be subsequently illustrated, that the compressor did not operate as efficiently as in the nominal engine.

The introduction of the exhaust gases into the inlet air by the bleedback system introduced both a variation in humidity and a contamination of the inlet air. For the range of temperatures presented, the variation of humidity amounted to about 15 grains per pound of air; as is shown later, this variation in humidity has no appreciable effect on engine performance. Theoretical considerations also

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indicate that the effects on performance due to variation in physical properties of the inlet air caused by exhaust-gas contamination are negligibly small.

Performance with Water-Alcohol Injection

Engine equipped with variable-area exhaust nozzle. - In figure 6, the compressor-pressure ratio P_2/P_1 is plotted against the inlet temperature T'_1 for a range of adjusted injected flows $(W_{al} + W_w)/\delta_1$ from 0 to 4 pounds per second varying from 100-percent water to a mixture of 40-percent water and 60-percent alcohol. These data were obtained at limiting conditions of 11,500 rpm and 1200° F tail-pipe temperature through adjustment of the exhaust-nozzle area. For a given compressor-inlet temperature, the nozzle area was reduced as the injected flow was increased, and for a given injected flow, the nozzle area was increased as the inlet temperature was increased.

As would be expected, the curves all show a downward trend of pressure ratio with increasing inlet temperature although the rate of decrease becomes less with increasing injected flow. At a constant compressor-inlet temperature, the pressure ratio increases with injected flow throughout the range investigated. This increase is a maximum with 100-percent water and becomes progressively smaller as the percentage of alcohol in the injected mixture is increased. This effect is particularly apparent at injected flows of 3 and 4 pounds per second but not at 2 pounds per second as the data scatter is greater than the trend. The curves for an injected flow of 2 pounds per second were faired in a manner consistent with the trends at 3 and 4 pounds per second. Only 100-percent water was injected at the rate of 1 pound per second.

With injection of 3 pounds per second of 100-percent water at compressor-inlet temperatures below 110° F, the engine fuel system could not supply sufficient fuel to maintain an indicated engine speed of 11,500 rpm and an indicated tail-pipe temperature of 1200° F. When this condition occurred, the tail-pipe temperature was maintained constant at the expense of engine speed and the results are denoted by the dashed portion of the curve in figure 6. This limit for any other engine would, of course, depend upon the fuel system design and the condition of the fuel strainers in the system.

Figure 7 presents the adjusted jet thrust F/δ_1 plotted against the compressor-pressure ratio for the data presented in figure 6. All data for the entire range of injected flows, mixture composition, and inlet temperatures correlate on a single line. The corrected thrust increases linearly from 1850 pounds at a compressor pressure ratio of 3.0 to about 3900 pounds at a compressor pressure ratio of 4.0. It is shown in appendix C that if engine speed, tail-pipe temperature, compressor-inlet pressure, and exhaust-nozzle ambient pressure are held constant, the jet thrust is primarily dependent upon the compressor-pressure ratio whether with or without injection at the compressor inlet. The dashed line in figure 7, which is a theoretical curve based upon constants applicable to the engine used in the investigation and obtained from the equations presented in appendix C, is in good agreement with the experimental curve. The experimental correlation of both normal and augmented thrust with compressor pressure ratio together with the good agreement with theory are particularly significant in performance estimation with inlet injection involving an engine using a variable-area exhaust nozzle. The results indicate, for example, that augmented engine performance for a wide range of conditions can be determined from brief engine tests without injection and component tests of compressor performance with injection.

Figure 8 shows the adjusted total weight flow $(W_a + W_{al} + W_w + W_f)/\delta_1$ plotted against compressor pressure ratio for the same data used in constructing figures 6 and 7. As in figure 7, there are no apparent trends with inlet temperature or inlet injection, with all of the data for the entire range of injected flow, mixture composition, and inlet temperature correlating on a single line. The adjusted total weight flow increases linearly from 59.5 pounds per second at a pressure ratio of 3.0 to 80 pounds per second at a pressure ratio of 4.0. The theoretical dashed curve shown on figure 8, which nearly coincides with the experimental curve, is based upon the same constants and sources of information used in constructing the theoretical curve shown on figure 7.

At a compressor-inlet temperature of 60° F, the normal compressor pressure ratio (fig. 6) is about 3.7. At a compressor-inlet temperature of 60° F, an engine speed of 11,500 rpm, and a tail-pipe temperature of 1200° F, which correspond to rated conditions, the compressor pressure ratio should be about 4.0 for this type engine. It is interesting to note also that at a compressor pressure ratio of 4.0 the jet thrust from figure 7 is 3900 pounds and the total weight flow of gases through the engine from figure 8 is 80 pounds per second. This thrust and weight flow closely correspond to the obtainable values at rated conditions for an efficient engine of the type used and indicate that low compressor efficiencies for the engine used in the runs reported herein were responsible for the low normal thrusts obtained.

The adjusted total liquid flow, which consists of the injected water and alcohol plus the fuel flow, is presented as a function of compressor-inlet temperature and injection rate in figure 9. For all injection rates and mixture compositions, the total liquid flow decreases linearly with increasing compressor-inlet temperature. At a given compressor-inlet temperature, the total liquid flow increases with injected flow and, for a given injected flow, decreases as the percent alcohol in the mixture is increased. This decrease in total liquid flow with increased alcohol content is caused primarily by the fact that the alcohol tends to burn and thus replace some of the fuel that would otherwise be required if no alcohol were present in the injected mixture. Inspection of figure 9 reveals that for injected mixtures containing about 70-percent water and 30-percent alcohol, the fuel flow at a given compressor-inlet temperature is nearly constant for all injection rates.

Inasmuch as the total liquid flow is a useful parameter to use in comparing methods of thrust augmentation, the results obtained in this investigation are presented on this basis in figure 10, which shows the adjusted jet thrust as a function of compressor-inlet temperature with total liquid flow as a parameter. The data of figures 6, 7, and 9 were used in the construction of this figure. When considered on this basis, all data for the various injected mixtures at a given total liquid flow defined a single curve. These results, which indicate that the thrust at a given compressor-inlet temperature is independent of injected liquid composition, are not in complete agreement with the results given in reference 2. The effects of injected liquid composition indicated in reference 2 were, however, very small and any such trend in the present data may have been obscured by the data scatter. The fact that all mixtures defined a single curve in figure 10, is, however, consistent with the results previously presented inasmuch as thrust was a function only of the compressor-pressure ratio and, at a constant injected flow and inlet temperature, an increase in alcohol concentration decreased both P_2/P_1 (and hence F/δ_1) and the total liquid flow. In figure 10, the curve labeled "normal" (no injection) is not for a fixed value of total liquid flow but is for the normal fuel flow of the engine at 11,500 rpm and 1200° F tail-pipe temperature over the range of compressor-inlet temperatures presented. As expected, the thrust at a given compressor-inlet temperature increases with total liquid flow. At a constant total liquid flow, the rate of decrease of thrust with increasing compressor-inlet temperature becomes progressively less as the total liquid flow increases.

The augmented thrust ratio (the ratio of thrust with injection at a given compressor-inlet temperature to the normal thrust at the same compressor-inlet temperature) as a function of compressor-inlet temperature is shown in figure 11(a). Two sets of curves are shown; the solid curves are for constant values of total liquid flow and the dashed curves are for constant values of augmented liquid ratio (the ratio of the total liquid flow to the normal fuel flow). As the inlet temperature is increased, the augmented thrust ratio is increased, particularly at the higher temperatures. The rate of this increase of augmented thrust ratio is progressively greater at higher values of both total liquid flow and augmented liquid ratio and is more pronounced for a constant total liquid flow than for a constant augmented liquid ratio. For an increase in compressor-inlet temperature from 60° F to 200° F, the augmented thrust ratio increased from 1.26 to 1.62 at a total liquid flow of 5 pounds per second and from 1.30 to 1.54 at an augmented liquid ratio of 5. The augmented thrust ratio as a function of compressor-inlet temperature at constant ratios of injected water flow to air flow is presented on figure 11(b). The data of figures 6, 7, 8, and 9 for the injection of 100 percent water were used in the construction of this figure. As shown on figure 11(b), the trends of augmented thrust ratio with compressor-inlet temperature at constant values of water-air ratio are similar to the trends at constant total liquid flow and augmented liquid ratio shown on figure 11(a).

It should be remembered that the augmented thrust ratios presented herein are for an engine with a relatively inefficient compressor and may be higher than would be obtained on an engine with normal compressor efficiencies.

Engine equipped with fixed-area exhaust nozzle. - A plot of jet thrust, engine speed, and tail-pipe temperature against compressor-inlet temperature for the runs with water injection during which the engine was equipped with a 19-inch fixed-area exhaust nozzle is shown in figure 12. As previously mentioned, for these runs the engine was operated at the limiting condition imposed by either a speed of 11,500 rpm or a tail-pipe temperature of 1200° F. As can be seen from the speed and tail-pipe temperature curves in figure 12, for a given injection rate there is only one compressor-inlet temperature at which the engine can be operated at limiting conditions of both speed and tail-pipe temperature. In the low inlet-temperature region, limiting speed was accompanied by less than rated tail-pipe temperatures, and in the high inlet-temperature region, limiting tail-pipe temperature was accompanied by less than rated engine speed. The compressor-inlet temperature for simultaneous operation at both limiting engine speed and tail-pipe temperature increased with injection rate. The characteristic downward trend of thrust with increasing compressor-inlet temperature becomes less pronounced as injection rate is increased. For the curve representing normal performance, a limiting compressor-inlet temperature is reached at approximately 145° F. At this temperature, which was obtained by extrapolation of generalized normal performance data, a region of operation is encountered in which the tendency of the tail-pipe temperature to exceed the limiting value of 1200° F as in the inlet temperature is further increased can no longer be compensated for by reductions in engine speed. A similar limiting inlet temperature would probably also be encountered for each injection rate, although not reached in this investigation.

Figure 13 presents the total liquid flow as a function of compressor-inlet temperature and injection rate for the runs using the fixed-area exhaust nozzle. At a given compressor-inlet temperature, the total liquid flow increases as the injected flow is increased; at a fixed value of injected flow the total liquid flow decreases linearly with increasing compressor-inlet temperature. These trends in total liquid flow with compressor-inlet temperature and injected flow are similar to those obtained (fig. 9) with the variable-area exhaust nozzle.

The adjusted jet thrust is presented as a function of the compressor-inlet temperature and the total liquid flow in figure 14. This figure is a cross plot of figures 12 and 13. The jet thrust increases with total liquid flow at a constant compressor-inlet temperature and decreases with compressor-inlet temperature at constant total liquid flow. These trends in thrust with compressor-inlet temperature and total liquid flow are similar to those obtained with the variable-area exhaust nozzle. For no injection, the decrease in thrust with increasing compressor-inlet temperature is much more pronounced for the fixed-area nozzle than for the variable-area nozzle, however, and as the total liquid flow increases, approaches the rate of decrease for the variable-area nozzle.

The augmented thrust ratio as a function of compressor-inlet temperature is presented on figure 15 for several values of total liquid flow and augmented liquid ratio. These curves are similar to those obtained for the variable-area exhaust nozzle in figure 11(a) except that the increase of augmented thrust ratio with increasing compressor-inlet temperature is much more pronounced for the fixed-area nozzle than for the variable-area nozzle. This greater effect of compressor-inlet temperature on the augmented thrust ratio is a reflection of the greater decrease in normal thrust for the engine equipped with a fixed-area nozzle than with the variable-area nozzle together with the fact that the effect of inlet temperature on thrust becomes more nearly equal for engines equipped with fixed- and variable-area nozzles as the rate of injection is increased. The curves are limited to a compressor-inlet temperature of approximately 145° F because normal operation (without injection) at temperatures higher than this was not possible. At a total liquid flow of 4 pounds per second, the augmented thrust ratio increases from 1.16 at a compressor-inlet temperature of 70° F to 1.71 at a compressor-inlet temperature of 145° F. These values of augmented thrust ratio are slightly lower than were obtained with the variable-area exhaust nozzle at 70° F but are about 27 percent greater at 145° F. The actual augmented thrust is, however, generally lower for the fixed-area nozzle than for the variable-area nozzle for the reasons previously discussed.

Effect of humidity. - The variation of compressor pressure ratio with compressor-inlet humidity is shown in figure 16 for constant rates of injection into the compressor inlet of 0, 1, and 2 pounds per second of water and for compressor-inlet temperatures of 125° F and 150° F. The range of specific humidities, from about 50 to 280 grains of water per pound of air, gave relative humidities less than 50 percent for all conditions shown on figure 16. In all cases, the compressor-pressure ratio decreases slightly with increasing humidity and the effects are somewhat more pronounced as the injection rate is increased. The decrease in pressure ratio with increasing humidity for no injection is in agreement with computed effects due to changes in physical properties of the air (R and c_p). These results, together with the thrust correlation of figure 7, show that increasing the inlet humidity from 60 grains per pound to 260 grains per pound results in thrust losses ranging from a minimum of 3.5 percent at a compressor-inlet temperature of 125° F with no injection to 7.7 percent at a compressor-inlet temperature of 150° F with the injection of 2 pounds per second at the compressor inlet. Because both the normal and augmented pressure ratio (hence thrust) decrease with increasing humidity, the augmented thrust ratio remains about constant for all conditions except for the injection of 2 pounds per second at a compressor-inlet temperature of 150° F for which a slight decrease in augmented thrust ratio is noted. These results showing, within the data scatter, a small effect of humidity on augmented thrust ratio, are in agreement with other unpublished data obtained at the Lewis laboratory on a similar type of engine.

SUMMARY OF RESULTS

An investigation at zero ram, sea-level pressure conditions was conducted to determine the effects of compressor-inlet temperature and humidity on performance with injection of water-alcohol mixtures at the compressor inlet of a centrifugal-flow-type turbojet engine equipped with both fixed- and variable-area exhaust nozzles. Water-alcohol mixtures injected contained 40, 60, 80, and 100 percent water and the injected rates were 1, 2, 3, and 4 pounds per second. Compressor-inlet temperatures ranged from 60° F to 230° F and compressor-inlet specific humidity ranged from 50 to 280 grains per pound of air. The following results were obtained in this investigation:

1. Normal engine performance (no injection) with a fixed-area exhaust nozzle was generalized by use of conventional performance parameters over a range of compressor-inlet temperatures from 70° F to 180° F.

2. At a given engine speed and tail-pipe temperature both the thrust and total weight flow for the complete range of compressor-inlet temperatures, injected mixtures, and injected flows investigated were functions only of the compressor pressure ratio. These results were substantiated by theoretical considerations.

3. The compressor pressure ratio, and hence the thrust, for the variable-area exhaust nozzle increased with injected flow and decreased with compressor-inlet temperature. The effect of inlet temperature on pressure ratio and thrust was less at high injection rates than at low injection rates. For a given injected flow, the compressor pressure ratio decreased with increasing alcohol content, but for a given total liquid flow (fuel plus injected coolant) the pressure ratio was independent of composition of the injected liquid.

4. For each injected flow, operation at simultaneous conditions of limiting speed and tail-pipe temperature with a fixed-area exhaust nozzle were obtained at only one compressor-inlet temperature. With a variable-area nozzle, however, limiting conditions of speed and tail-pipe temperature, and hence maximum thrust output, could be maintained over the complete range of inlet temperatures of the investigation.

5. The augmented thrust ratio (ratio of augmented to normal thrust) was greatest at high inlet temperatures and injected flows. For a given inlet temperature and injected flow, the augmented thrust

ratio was higher for the fixed-area exhaust nozzle than for the variable-area nozzle but the actual thrust produced was generally less for the fixed-area nozzle than for the variable-area nozzle.

6. At a total liquid flow of 5 pounds per second, the augmented thrust ratio obtained when a variable-area exhaust nozzle was used increased from 1.26 to 1.62 as the compressor-inlet temperature was increased from 60° F to 200° F.

7. At a given inlet temperature and injection rate, the compressor pressure ratio decreased slightly with increasing humidity of the inlet air with the effects becoming more pronounced at the higher injection rates.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

APPENDIX A

DETERMINATION OF JET THRUST

For the investigation covered in this report, the values of thrust measured by the thrust measuring system had to be corrected for the influence of the exhaust-gas outlet manifold and deflection plate located ahead of the inlet cowl in order to obtain values of jet thrust. The exhaust-gas outlet manifold and deflection plate, which were mounted rigidly to the test cell floor, created a loss in total pressure of the air entering the inlet cowl, resulting in a cowl-inlet momentum lower than that in the test cell which is customarily used as a reference in determining jet thrust. These thrust corrections are equal in magnitude to the product of the cowl inlet area and the difference between the cell static pressure and the average total pressure in the plane of the cowl inlet, and were subtracted from the value obtained from the thrust mechanism. It was found by calibration that there were no measurable differences between the cowl-inlet and engine-inlet total pressures and these latter pressures were used for computation of the corrections. The magnitude of this thrust correction ranged from 60 to 250 pounds for the test conditions covered.

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APPENDIX B

COMPUTATION OF INLET-AIR HUMIDITY

The inlet-air humidity, for the investigation of the effects of this variable, was determined by measurement of all factors that influenced the amount of water vapor entering the cowl inlet. The following equation was used for this determination:

$$W_{s,0} = \left[\left(\frac{W_b}{W_7}\right) + \left(\frac{W_b}{W_7}\right)^2 + \left(\frac{W_b}{W_7}\right)^3 + \cdot \cdot \cdot\right] \left[W_{s,h} + \frac{W_N\left(\frac{W_{s,a}}{W_a}\right)}{1 + \left(\frac{W_{s,a}}{W_a}\right)} + W_{s,1} + W_{s,f}\right]$$

$$+ \left[W_{s,h} + \frac{W_N\left(\frac{W_{s,a}}{W_a}\right)}{1 + \left(\frac{W_{s,a}}{W_a}\right)}\right]$$

where

$W_{s,0}$ weight flow of superheated water vapor entering the cowl, (lb)/(sec)

W_7 total weight flow through engine, (lb)/(sec)

W_b total weight flow through bleedback system, (lb)/(sec)

$W_{s,h}$ weight flow of water injected into bleedback system, (lb)/(sec)

W_N weight flow of air and water vapor through main air measuring nozzle, (lb)/(sec)

$\frac{W_{s,a}}{W_a}$ specific humidity of W_N, (lb-water)/(lb-air)

$W_{s,f}$ weight of water vapor formed by fuel combustion, (lb)/(sec)

$W_{s,1}$ weight of water injection into the compressor inlet, (lb)/(sec)

All terms appearing in this equation except $W_{s,a}/W_a$ and $W_{s,f}$ were measured directly. $W_{s,a}/W_a$ was obtained from a psychrometric chart by use of wet and dry bulb temperatures and $W_{s,f}$ was taken as 1.237 times the fuel flow. The factor 1.237 results from the chemical equilibrium of combustion of a fuel with a composition of $C_{12}H_{26}$ at an assumed combustion efficiency of 90 percent. The series appearing in the first bracket on the right hand side of the previous equation accounts for the continued recirculation through the engine and bleedback system of a portion of the various humidities. Because the series converges for all values of W_b/W_7 less than one, the recirculation reached a stabilized value.

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APPENDIX C

BASIS FOR GENERALIZATION OF THRUST AND WEIGHT-FLOW DATA

WITH INJECTION AT THE COMPRESSOR INLET

Generalization of the thrust data for the compressor-inlet injection investigation with the variable-area exhaust nozzle was supported by the following analytical treatment in which the changes occurring in the physical properties of the working fluid from station to station in the engine are temporarily neglected.

The jet thrust is given by

$$F = \frac{W_7}{g} V_8 \tag{1}$$

where

$$W_7 = W_5 = \frac{\rho_5 A_5 V_5}{144} = \frac{p_5 A_5 V_5}{R t_5} \tag{2}$$

and

$$V_8 = \sqrt{2\eta_n \, gJc_p \, T_7 \left[1 - \left(\frac{p_8}{P_7}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{3}$$

The turbine-nozzle-throat velocity V_5 may be expressed as

$$V_5 = \sqrt{2gJc_p \, T_5 \left[1 - \left(\frac{p_5}{P_5}\right)^{\frac{\gamma-1}{\gamma}}\right]} \tag{4}$$

At station 5, isentropically

$$t_5 = T_5 \left(\frac{p_5}{P_5}\right)^{\frac{\gamma-1}{\gamma}} \tag{5}$$

Combining equations (2), (4), and (5) gives

$$W_7 = \frac{P_5 \left(\frac{p_5}{P_5}\right)^{\frac{1}{\gamma}} A_5 \sqrt{2gJc_p \left[1 - \left(\frac{p_5}{P_5}\right)^{\frac{\gamma-1}{\gamma}}\right]}}{R\sqrt{T_5}} \tag{6}$$

If the mechanical work of friction, oil and fuel pumping, etc. are neglected the turbine work equals the compressor work, or

$$W_2\ Jc_p\ (T_2 - T_1) = W_5\ Jc_p\ (T_5 - T_7) \tag{7}$$

From continuity

$$W_5 = W_2 + W_f = W_2 \left(1 + \frac{W_f}{W_2}\right) \tag{8}$$

From the adiabatic work of compression

$$Jc_p\ (T_2 - T_1) = K \frac{\left(\frac{\pi DN}{60}\right)^2}{g} \tag{9}$$

Combining equations (7), (8), and (9) yields

$$K \frac{\left(\frac{\pi DN}{60}\right)^2}{g} = \left(1 + \frac{W_f}{W_2}\right) Jc_p\ (T_5 - T_7) \tag{9}$$

or

$$T_5 = T_7 + \frac{K \left(\frac{\pi DN}{60}\right)^2}{gJc_p \left(1 + \frac{W_f}{W_2}\right)} \tag{9a}$$

Combining equations (1), (3), (6), and (9a) and substituting $14.696 \left(\frac{P_1}{14.696}\right)\left(\frac{P_2}{P_1}\right)\left(\frac{P_5}{P_2}\right)$ for P_5 yields

$$\frac{F}{\delta_1} = \frac{14.696\left(\frac{P_2}{P_1}\right)\left(\frac{P_5}{P_2}\right)\left(\frac{p_5}{P_5}\right)^{\frac{1}{\gamma}} A_5 \; 2Jc_p\sqrt{\eta_n\; T_7\left[1 - \left(\frac{p_5}{P_5}\right)^{\frac{\gamma-1}{\gamma}}\right]\left[1 - \left(\frac{p_8}{P_7}\right)^{\frac{\gamma-1}{\gamma}}\right]}}{R\sqrt{T_7 + \frac{K\left(\frac{\pi DN}{60}\right)^2}{gJc_p\left(1 + \frac{W_f}{W_2}\right)}}} \tag{10}$$

In equation (10), p_8/P_7 may be expressed as

$$\frac{p_8}{P_7} = \frac{1}{\left(\frac{P_7}{P_5}\right)\left(\frac{P_5}{P_2}\right)\left(\frac{P_2}{P_1}\right)\left(\frac{P_1}{p_8}\right)} \tag{11}$$

An expression to eliminate P_7/P_5 from equation (11) (and hence from equation (10)) may be obtained as follows:

By definition

$$T_5 - T_7 = \eta_T\; T_5\left[1 - \left(\frac{P_7}{P_5}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{12}$$

Combining equations (9a) and (12) yields

$$\left(\frac{P_7}{P_5}\right)^{\frac{\gamma-1}{\gamma}} = 1 - \frac{\left[\frac{K\left(\frac{\pi DN}{60}\right)^2}{gJc_p\left(1 + \frac{W_f}{W_2}\right)}\right]}{\eta_T\left[T_7 + \frac{K\left(\frac{\pi DN}{60}\right)^2}{gJc_p\left(1 + \frac{W_f}{W_2}\right)}\right]} \tag{13}$$

Equations (10), (11), and (13) can be combined to give the following functional relation:

$$\frac{F}{\delta_1} = f\left(\frac{P_2}{P_1}, T_7, K, N, D, \frac{P_5}{p_5}, \frac{P_5}{P_2}, \frac{P_1}{p_8}, \frac{W_f}{W_2}, \eta_T, A_5, \eta_n, c_p, \gamma, R\right) \tag{14}$$

If the turbine nozzles are choked, P_5/p_5 would be dependent only upon the physical properties at station 5 in the engine. If the turbine nozzles are not choked P_5/p_5 would be a function of P_7/P_5 and hence, as equation (13) shows, a function of terms already appearing in equation (14). For a given engine, D and A_5 can be eliminated as constants. P_5/P_2 would be primarily dependent upon the construction of the burner and the regime of operation of the turbine nozzles; a secondary function would be the temperature ratio across the burner, which would be a function of W_f/W_2. Thus, P_5/P_2 is a function of terms already appearing in equation (14) as was the case for P_5/p_5. The turbine efficiency η_T is a function of the turbine tip speed T_5 and P_7/P_5 and hence, as can be seen from equations (12) and (13), is finally dependent only on N, T_7, W_f/W_2, and the physical properties at station 5; these terms already appear in the functional relationship of equation (14). The exhaust nozzle efficiency η_n can be considered as constant.

Equation (14) could therefore be simplified to the form

$$\frac{F}{\delta_1} = f\left(\frac{P_2}{P_1}, T_7, K, N, \frac{W_f}{W_2}, \frac{P_1}{p_8}, c_p, \gamma, R\right) \tag{14a}$$

It would be expected that only minor trends would be introduced by the variables W_f/W_2, the physical properties of the working fluid, and K. Thus at constant values of N, T_7, and P_1/p_8, (characteristic of variable-area exhaust nozzle data presented in this report) the above equation suggests that F/δ_1 is a function primarily of P_2/P_1.

The weight flow through the engine can be handled in a similar manner. Combining equations (6) and (9a) and substituting

$$14.696\left(\frac{P_1}{14.696}\right)\left(\frac{P_2}{P_1}\right)\left(\frac{P_5}{P_2}\right)$$ for P_5 yields

$$\frac{W_7}{\delta_1} = \frac{14.696\left(\frac{P_2}{P_1}\right)\left(\frac{P_5}{P_2}\right)\left(\frac{p_5}{P_5}\right)^{\frac{1}{\gamma}} A_5 \sqrt{2\ gJc_p\left[1 - \left(\frac{p_5}{P_5}\right)^{\frac{\gamma-1}{\gamma}}\right]}}{R\sqrt{T_7 + \frac{K\left(\frac{\pi DN}{60}\right)^2}{gJc_p\left(1 + \frac{W_f}{W_2}\right)}}} \tag{15}$$

Equation (15) and application of reasoning similar to that following equation (14) leads to the following simplified functional relation:

$$\frac{W_7}{\delta_1} = f\left(\frac{P_2}{P_1}, T_7, K, N, \frac{W_f}{W_2}, c_p, \gamma, R\right) \tag{16}$$

Thus, at constant values of N, T_7, and P_1/p_8, as for thrust, equation (16) indicates that W_7/δ_1 is primarily dependent upon P_2/P_1.

By substitution of $P_5/P_2 = 0.95$, $\gamma = 1.34$, $c_p = 0.27$, $A_5 = 122$, $\eta_n = 0.95$, $T_7 = 1660$, $P_1 = p_8$, $\eta_T = 0.80$, $K = 0.95$, $\pi DN/60 = 1500$, $W_f/W_2 = 0.016$ in equations (10), (11), (13), and (15) and assuming choked flow through the turbine nozzles, the following expressions may be obtained:

$$\frac{F}{\delta_1} = 2875\left(\frac{P_2}{P_1}\right)\sqrt{1 - \frac{1.269}{\left(\frac{P_2}{P_1}\right)^{.254}}}$$

$$\frac{W_7}{\delta_1} = 20.0\left(\frac{P_2}{P_1}\right)$$

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These expressions are applicable to the engine used and conditions encountered in the tests covered in this report and were used to obtain the theoretical curves shown on figures 7 and 8.

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2. Jones, William L., and Engelman, Helmuth W.: Experimental Investigation of Thrust Augmentation of 4000-Pound-Thrust Centrifugal-Flow-Type Turbojet Engine by Injection of Water and Alcohol at Compressor Inlets. NACA RM E7J19, 1948.

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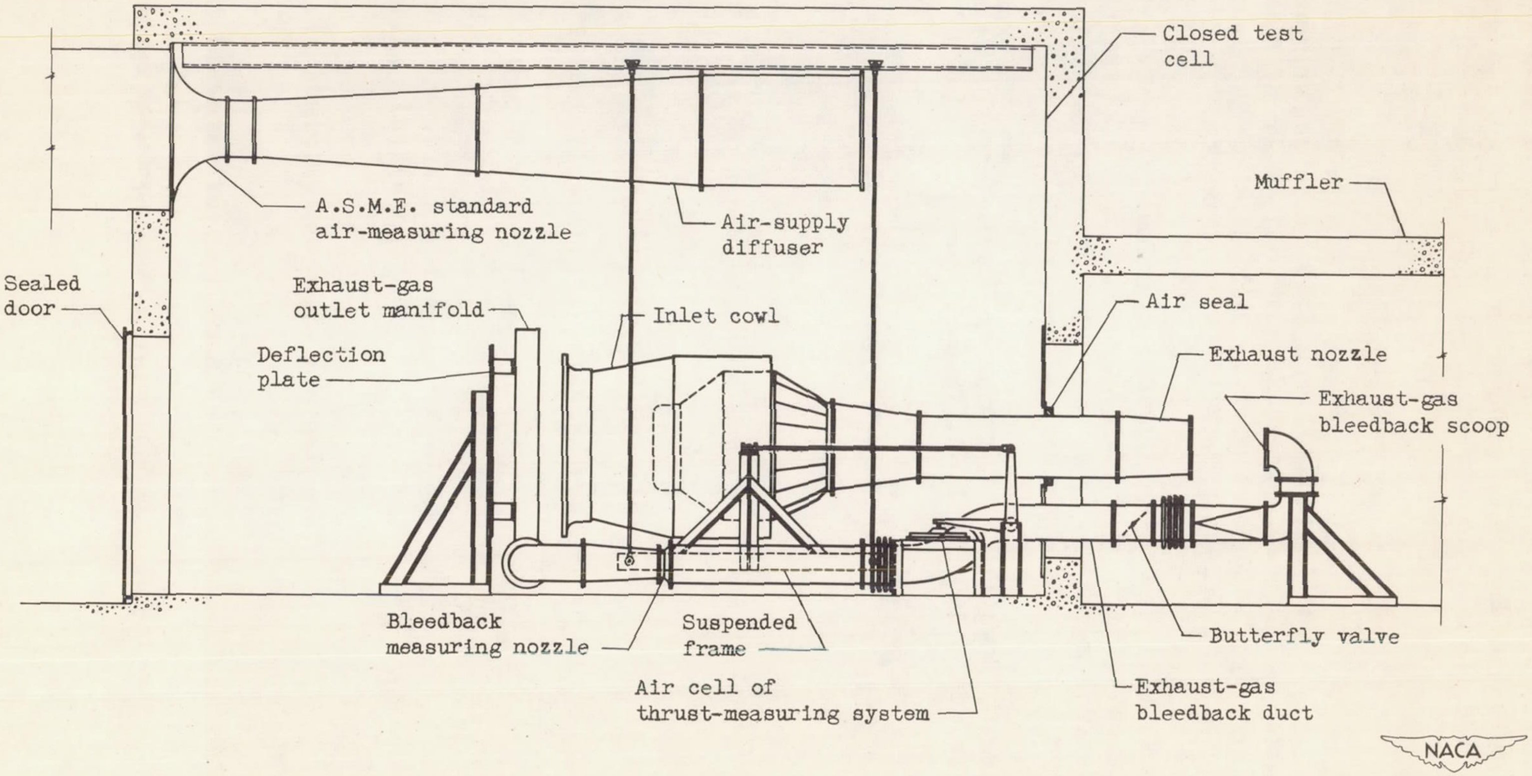


Figure 1. - Diagram of setup for investigation of effect of inlet temperature and humidity on thrust augmentation by compressor-inlet injection.

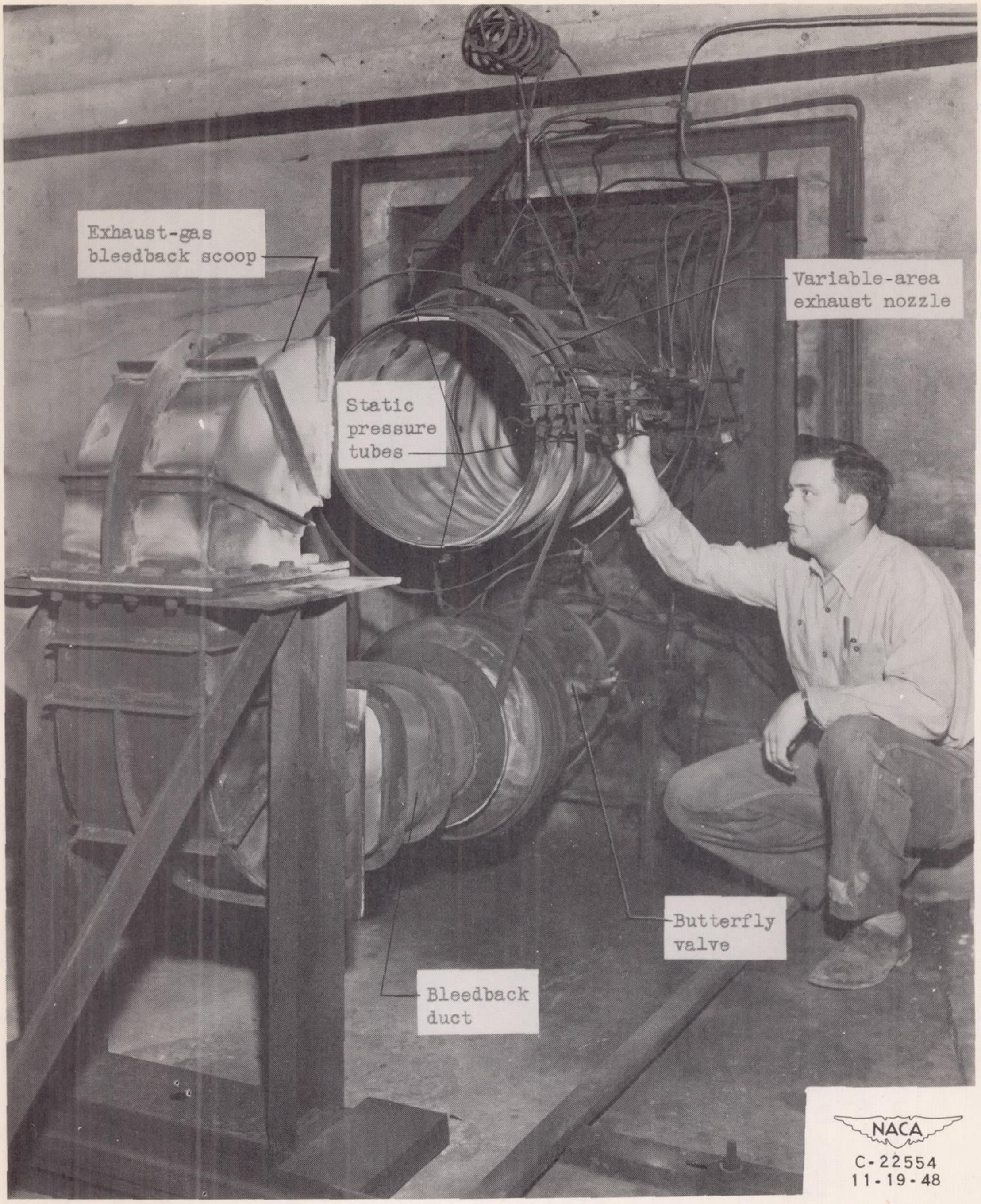


Figure 2. - View in muffler showing engine exhaust nozzle and exhaust-gas bleedback scoop.

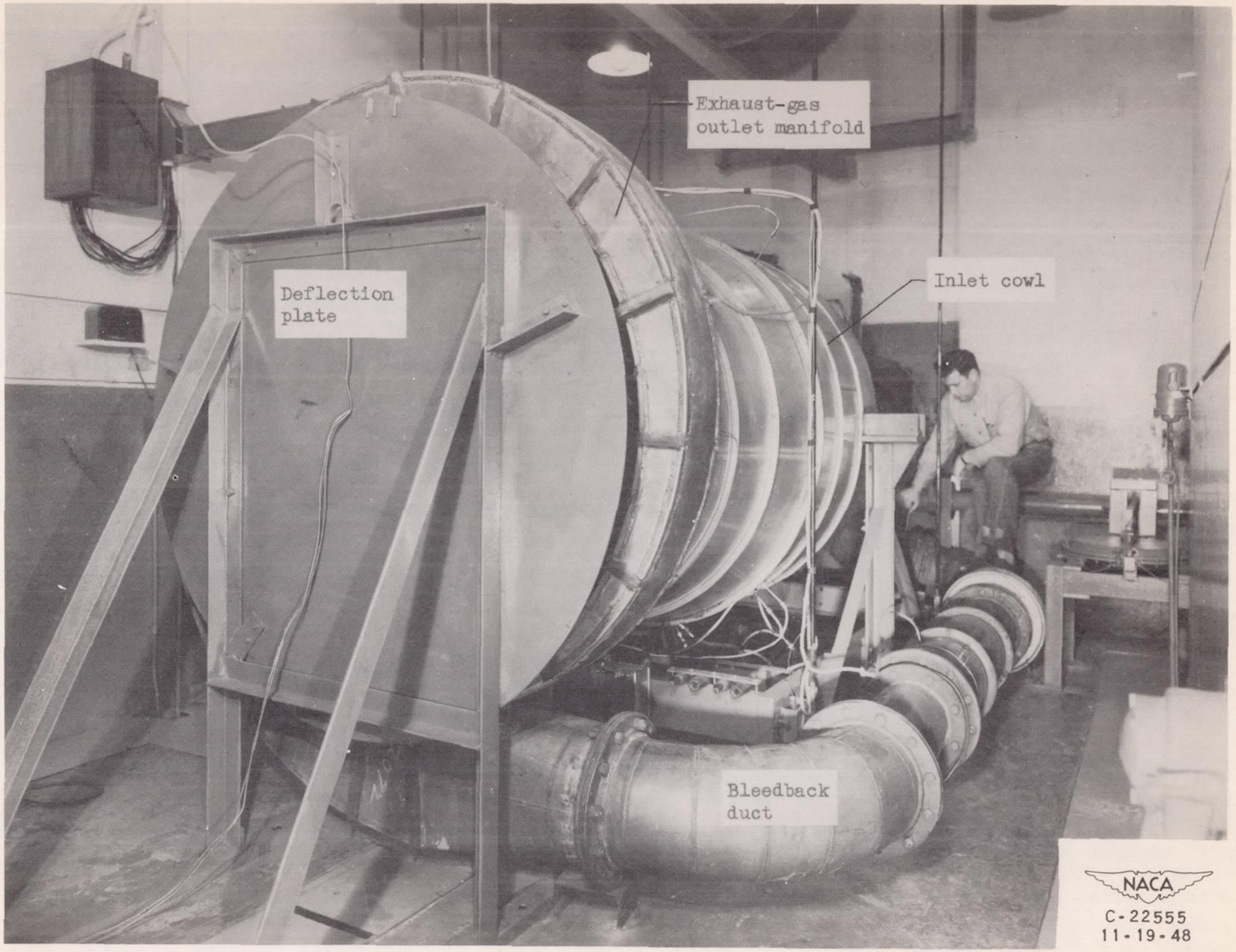


Figure 3. - View of equipment in test cell looking aft.

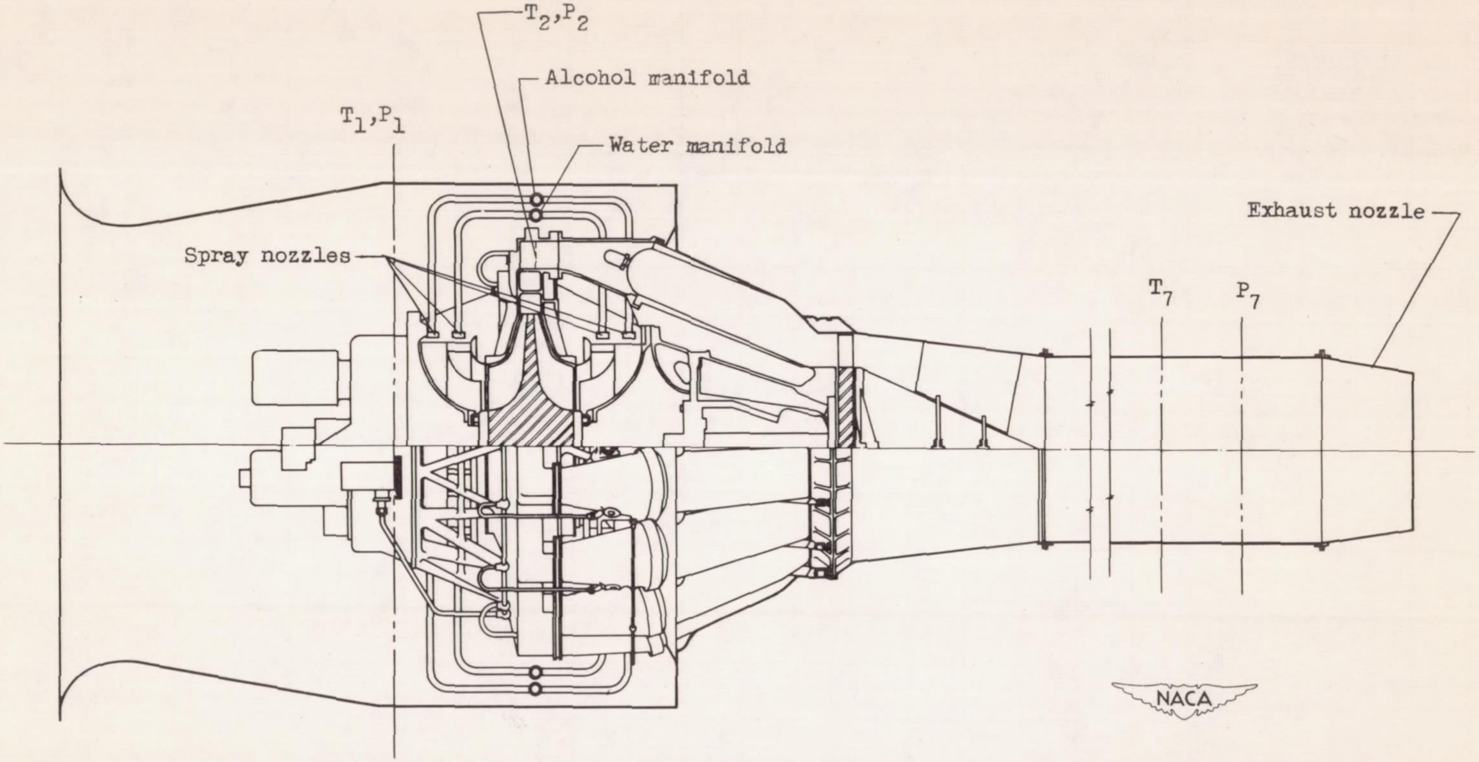


Figure 4. - Instrumentation stations and injection equipment for investigation of effect of inlet temperature and humidity on thrust augmentation by compressor-inlet injection.

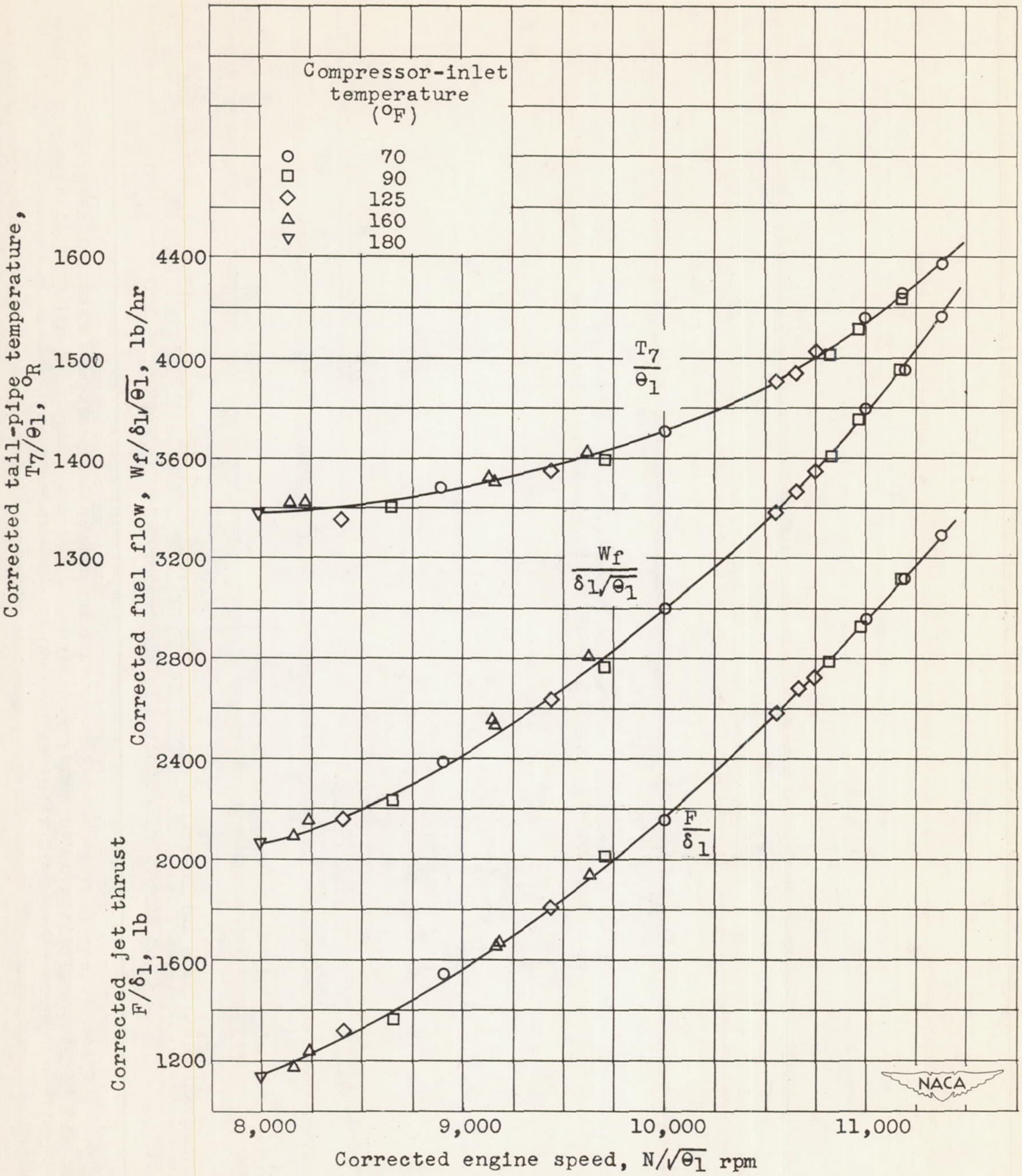


Figure 5. - Effect of engine speed on thrust, fuel flow, and tail-pipe temperature at several compressor-inlet temperatures. Engine equipped with 19-inch fixed-area exhaust nozzle. No injection.

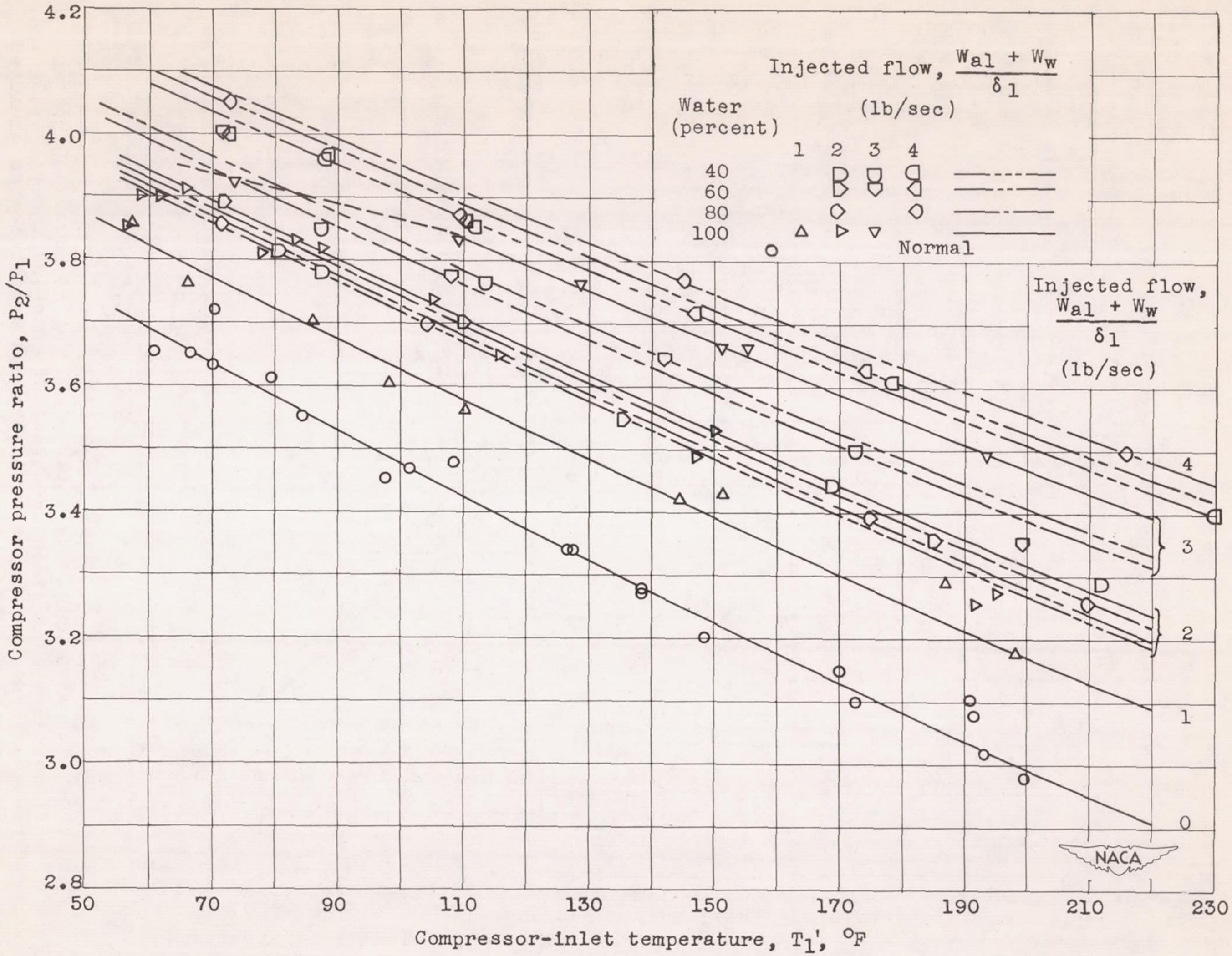


Figure 6. - Effect of compressor-inlet temperature on compressor pressure ratio at several injected flows and for several mixtures of water and alcohol. Engine speed, 11,500 rpm; tail-pipe temperature, 1200° F. Engine equipped with variable-area exhaust nozzle.

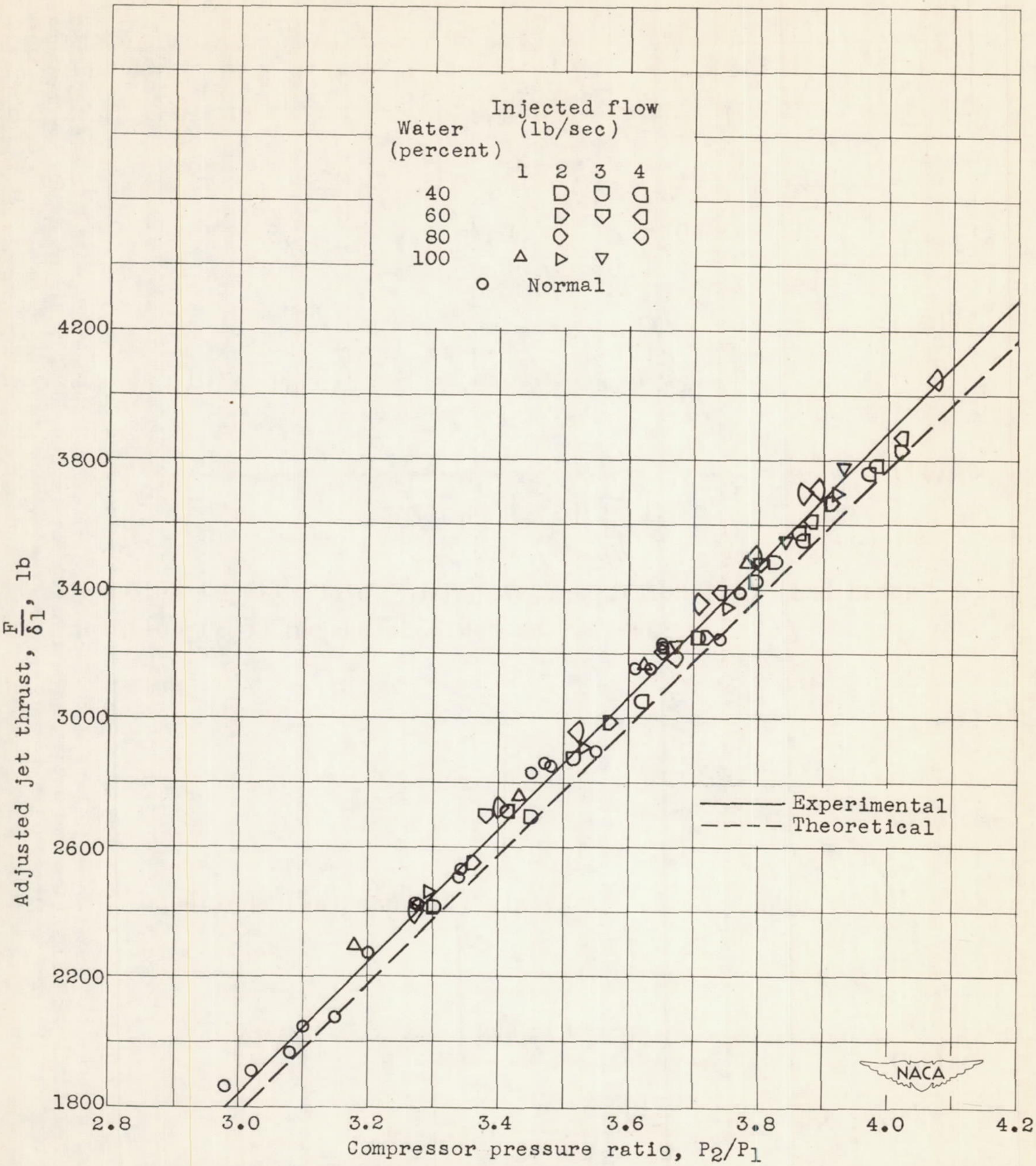


Figure 7. - Effect of compressor pressure ratio on thrust at several injected flows and for several mixtures of water and alcohol. Engine speed, 11,500 rpm; tail-pipe temperature, 1200° F. Engine equipped with variable-area exhaust nozzle.

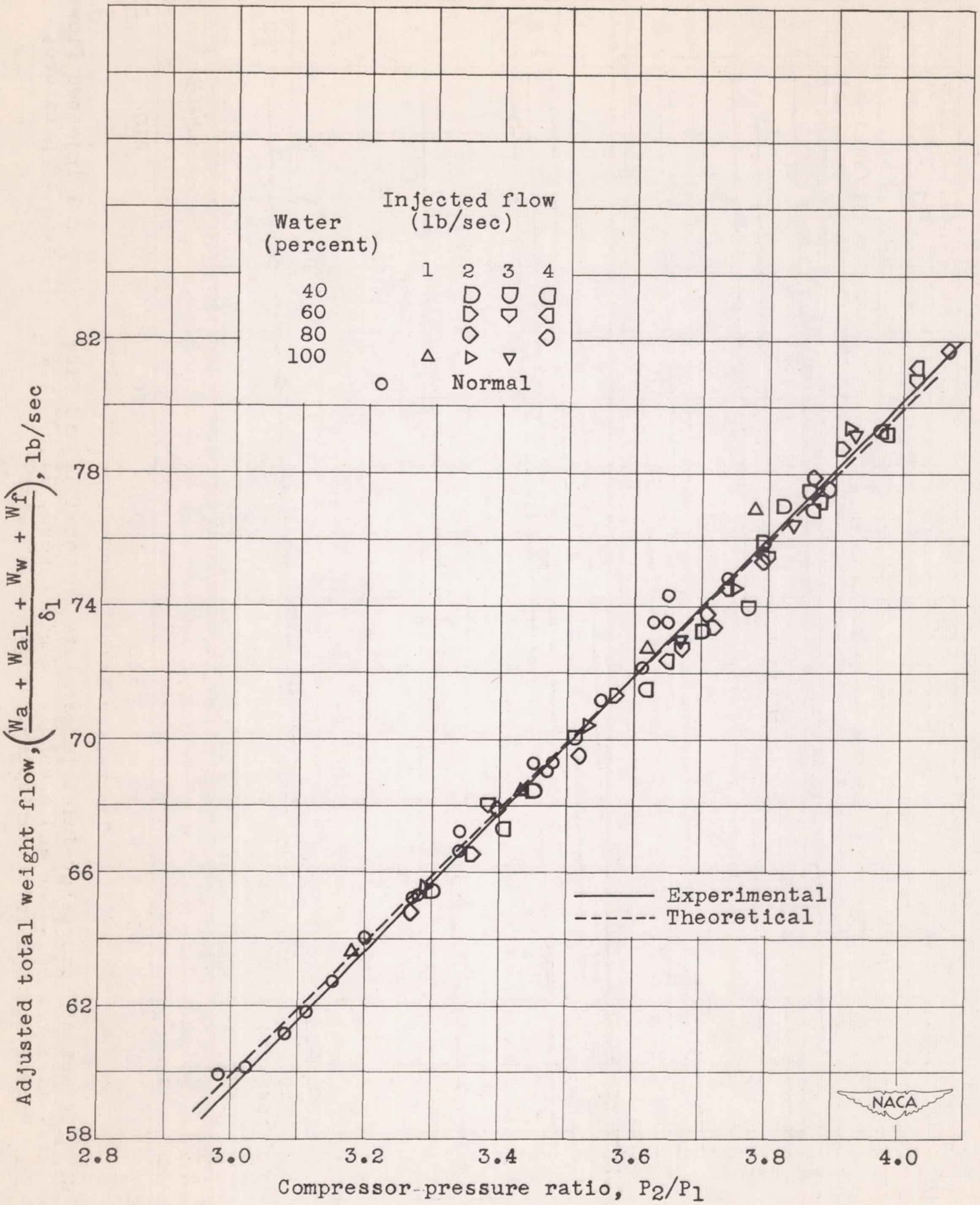


Figure 8. - Effect of compressor-pressure ratio on total weight flow at several injected flows and for several mixtures of water and alcohol. Engine speed, 11,500 rpm; tail-pipe temperature, 1200° F. Engine equipped with variable-area exhaust nozzle.

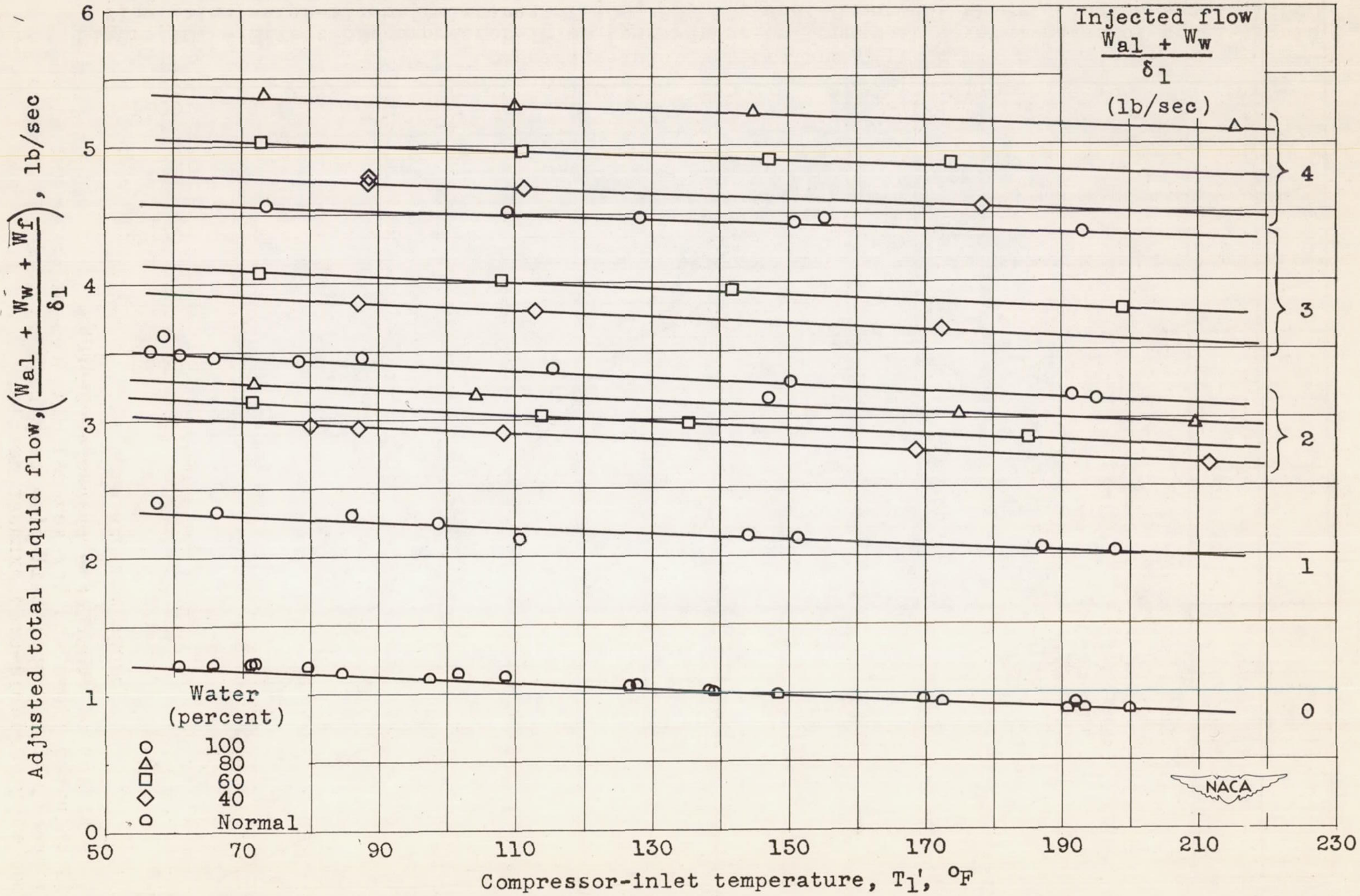


Figure 9. - Effect of compressor-inlet temperature on total liquid flow at several injected flows and several mixtures of water and alcohol. Engine speed, 11,500 rpm; tail-pipe temperature, 1200° F. Engine equipped with variable-area exhaust nozzle.

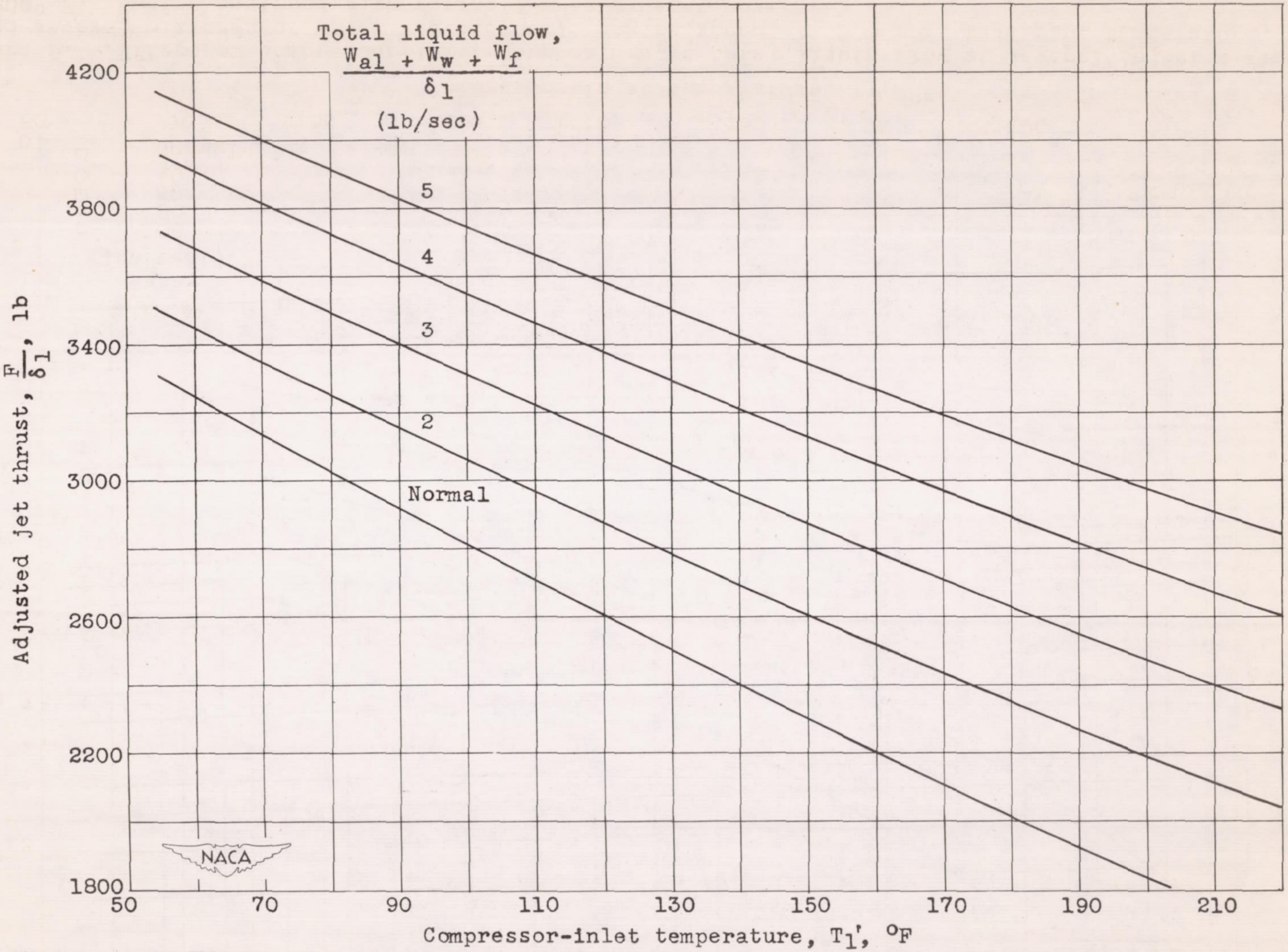
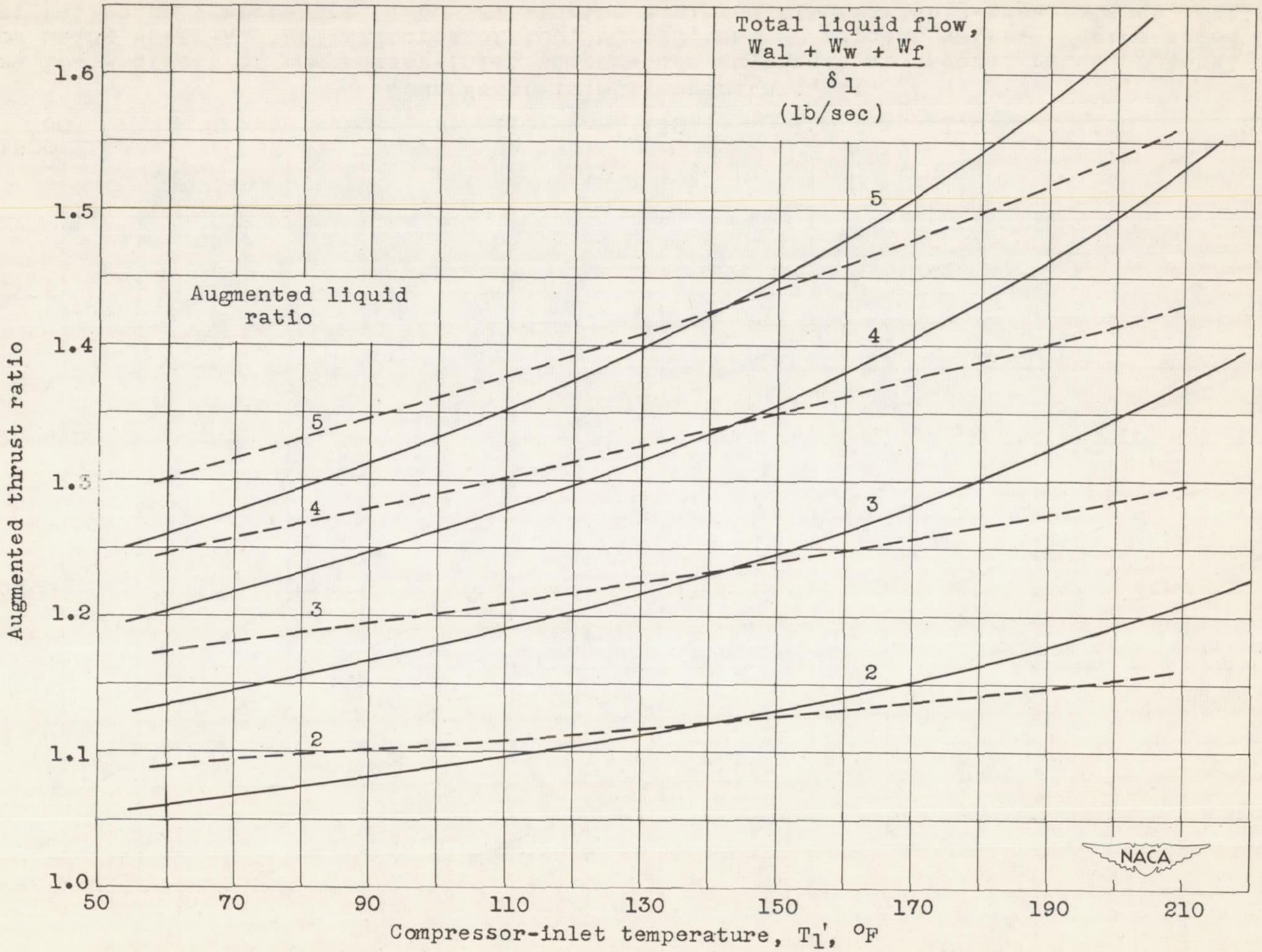
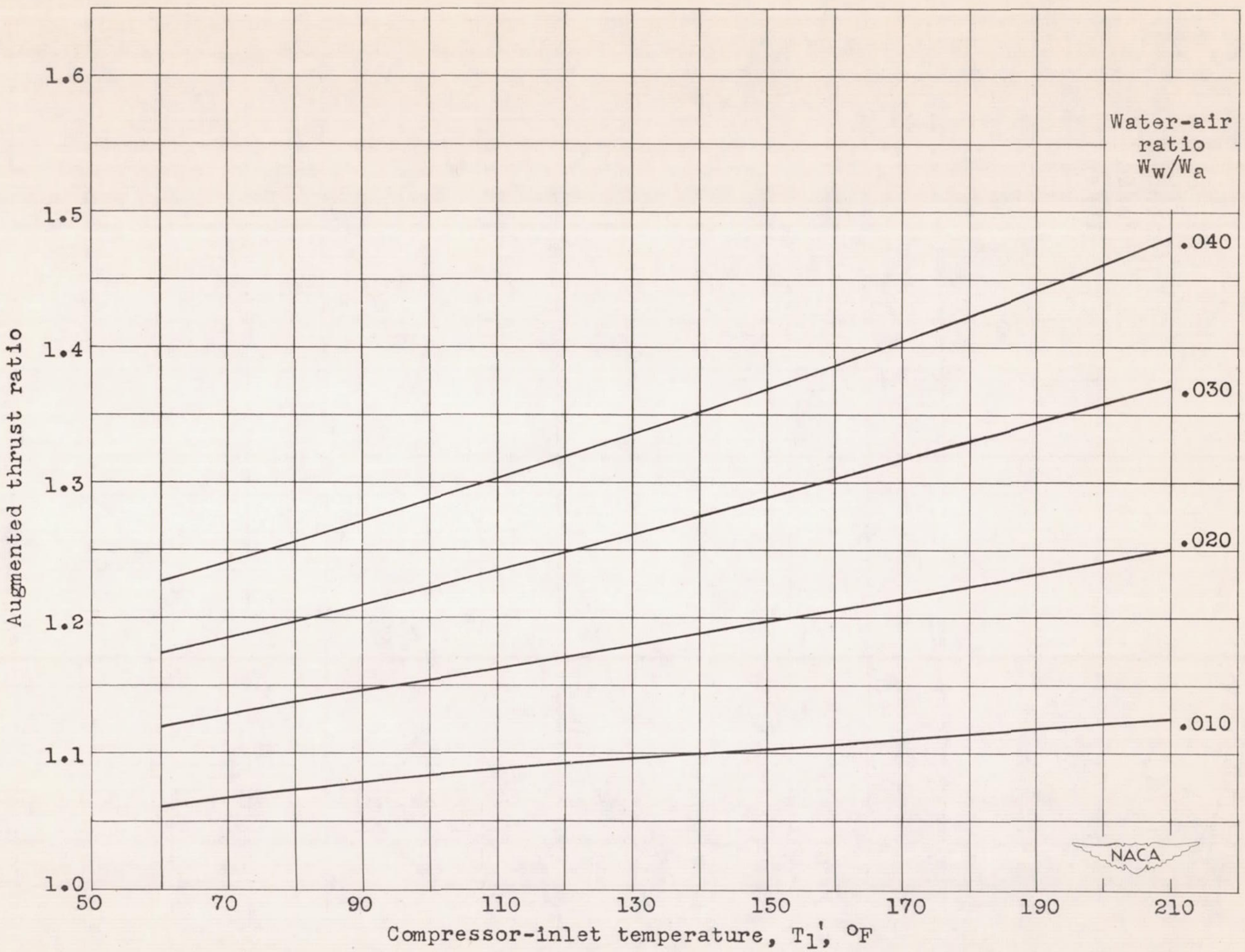


Figure 10. - Effect of compressor-inlet temperature on thrust at several rates of total liquid flow using water-alcohol mixtures of 100, 80, 60, and 40 percent water. Engine speed 11,500 rpm; tail-pipe temperature, 1200 F. Engine equipped with variable-area exhaust nozzle.



(a) For several values of total liquid flow and augmented liquid ratio. Water-alcohol mixtures of 100, 80, 60, and 40 percent water.

Figure 11. - Effect of compressor-inlet temperature on augmented thrust ratio. Engine speed, 11,500 rpm; tail-pipe temperature, 1200 F. Engine equipped with variable-area exhaust nozzle.



(b) For several values of water-air ratio. 100-percent water.

Figure 11. - Concluded. Effect of compressor-inlet temperature on augmented thrust ratio. Engine speed, 11, 500 rpm; tail-pipe temperature, 1200° F. Engine equipped with variable-area exahsut nozzle.

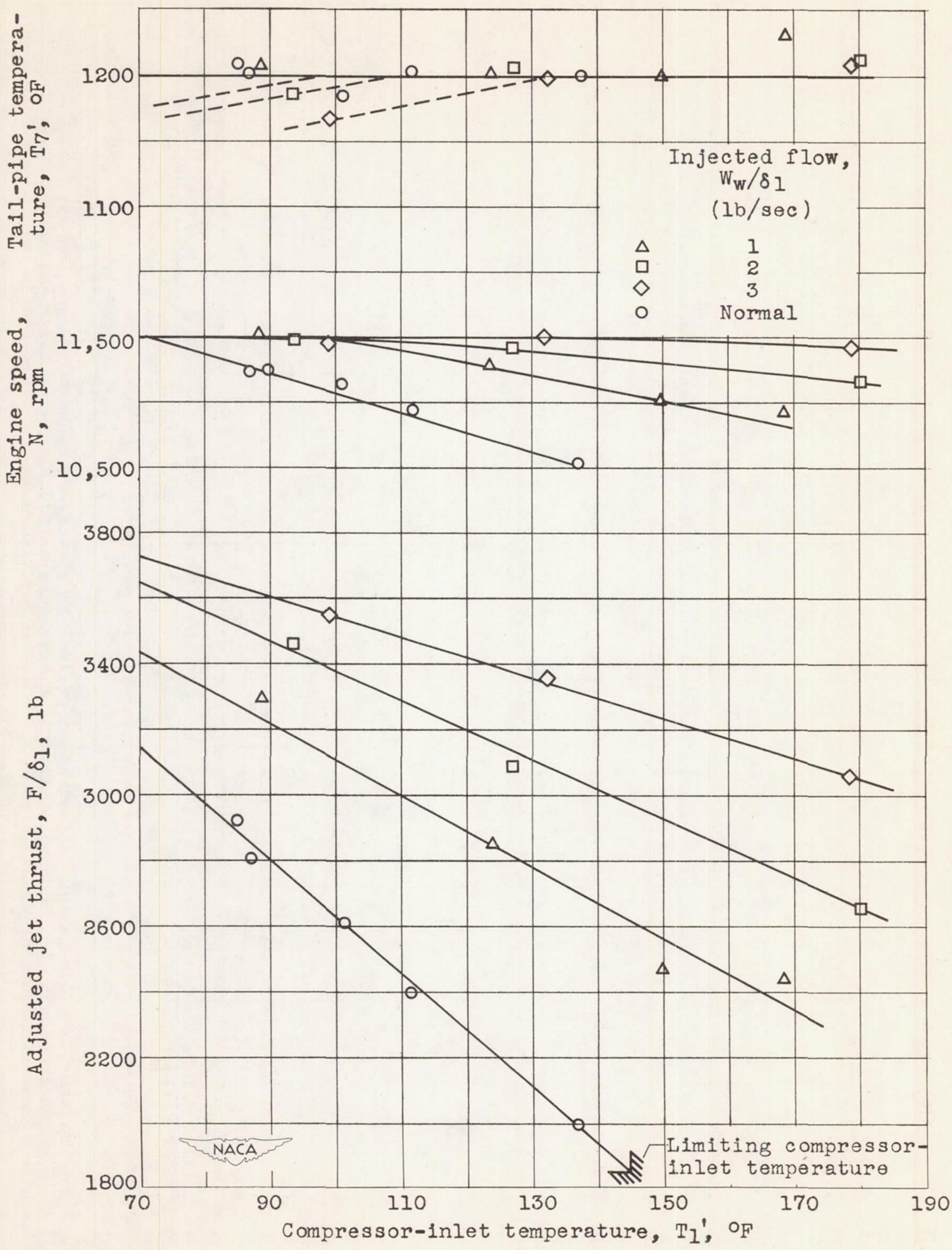


Figure 12. - Effect of compressor-inlet temperature on thrust, engine speed, and tail-pipe temperature, at several injected flows using 100-percent water. Engine equipped with 19-inch fixed-area exhaust nozzle.

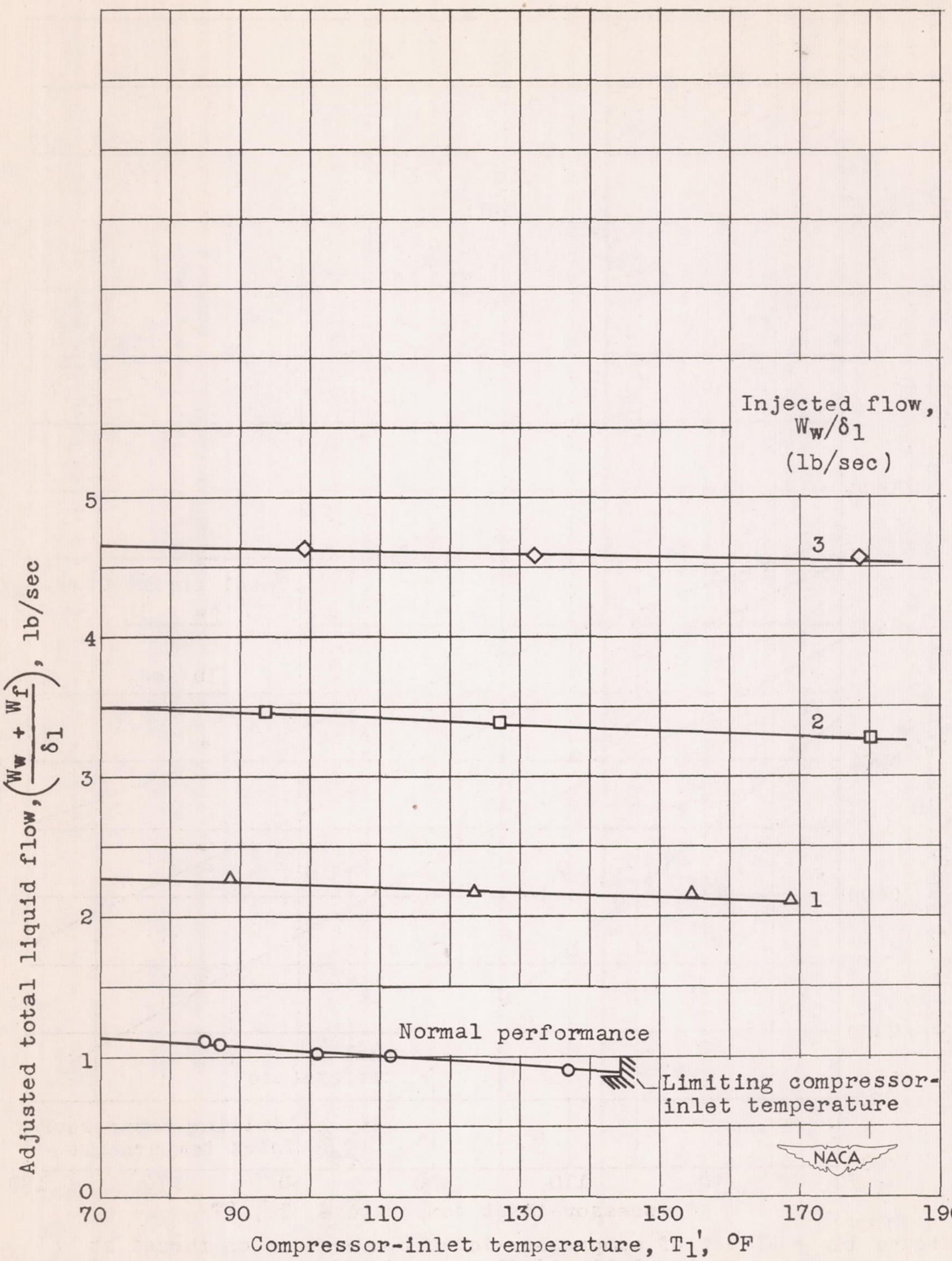


Figure 13. - Effect of compressor-inlet temperature on total liquid flow at several injected flows using 100-percent water. Engine equipped with 19-inch fixed-area exhaust nozzle.

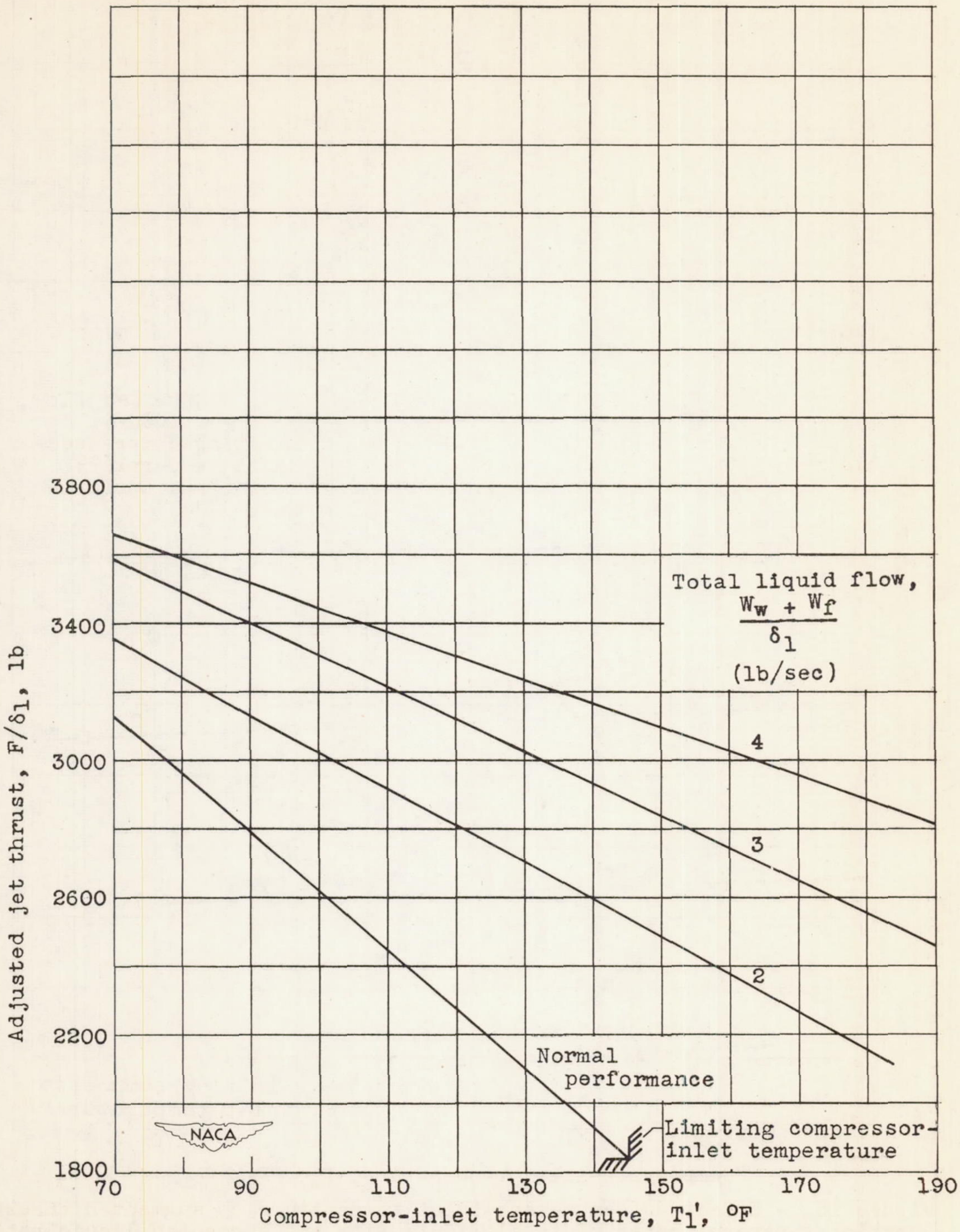


Figure 14. - Effect of compressor-inlet temperature on thrust at several rates of total liquid flow using 100-percent water. Engine equipped with 19-inch fixed-area exhaust nozzle.

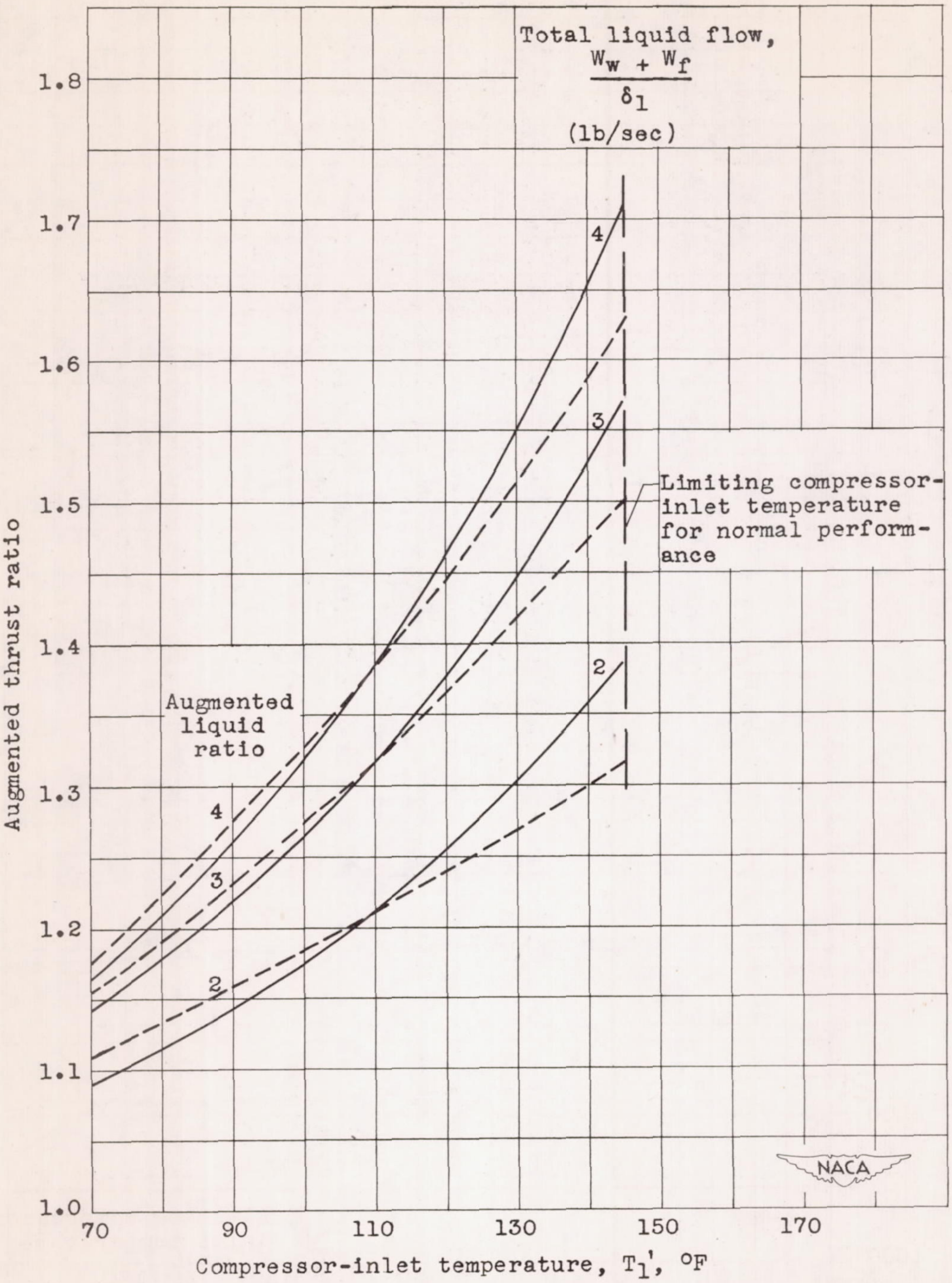
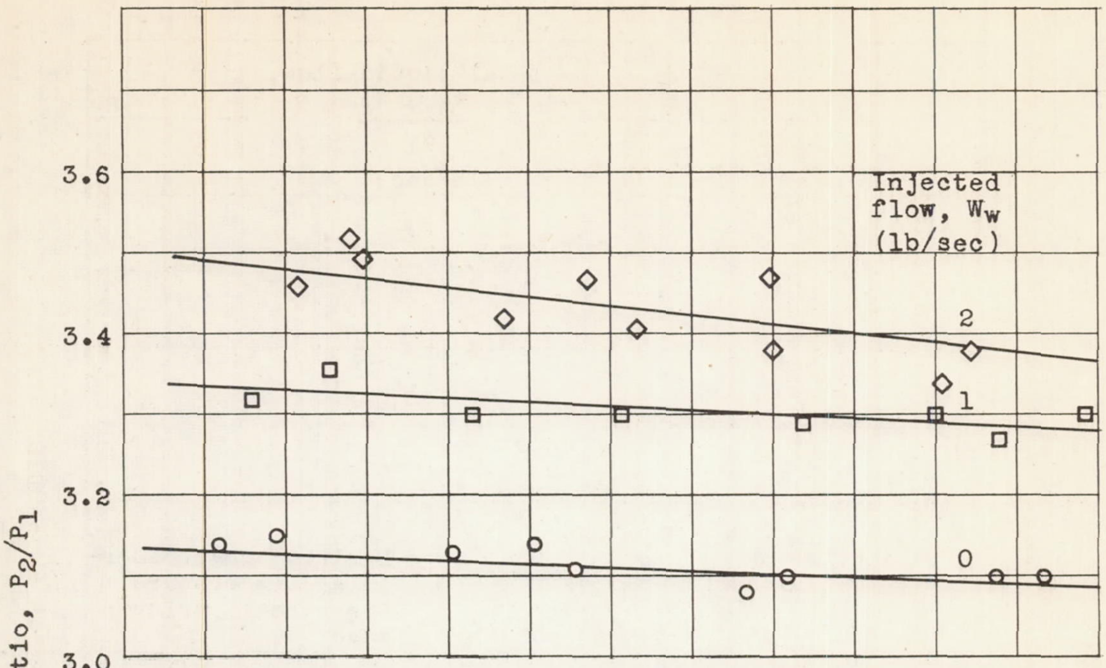
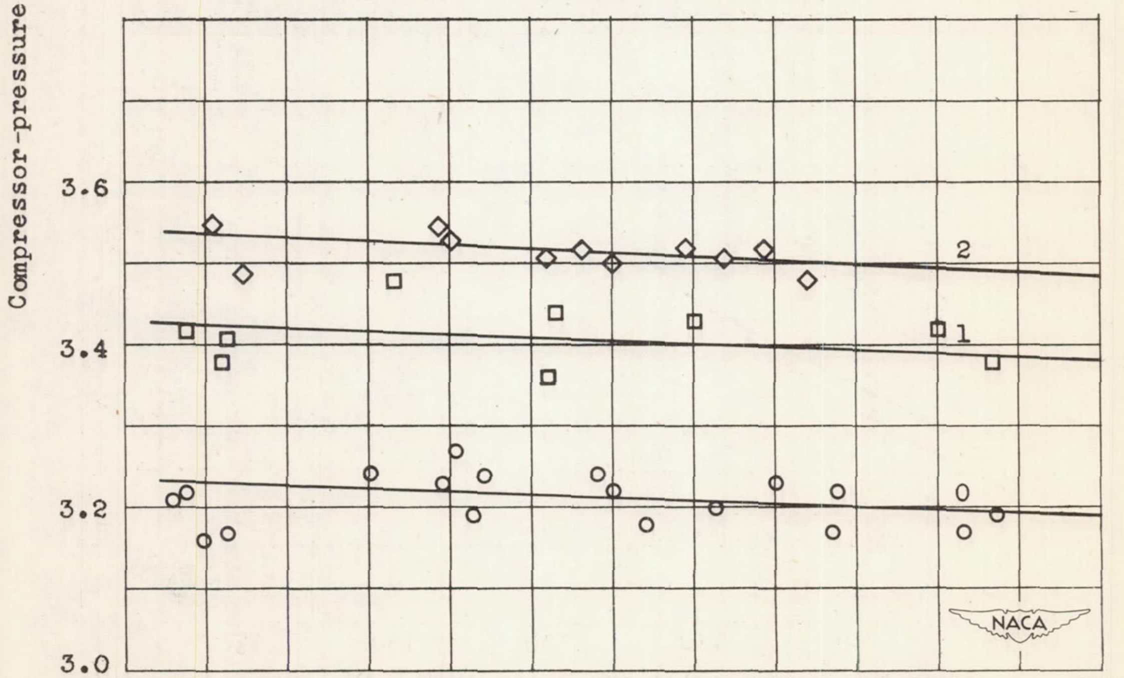


Figure 15. - Effect of compressor-inlet temperature on augmented thrust ratio at several rates of total liquid flow and augmented liquid ratio using 100-percent water. Engine equipped with 19-inch fixed-area exhaust nozzle.



(a) Compressor-inlet temperature, T_1', 150° F.



(b) Compressor-inlet temperature, T_1', 125° F

Figure 16. - Effect of humidity on compressor pressure ratio at several injected flows using 100-percent water. Engine speed, 11,500 rpm; tail-pipe temperature, 1200° F. Engine equipped with variable-area exhaust nozzle.